

Abstract for Invited Lecture to be presented at
10th CEAS-ASC Workshop on Jet Noise Prediction Methodologies, Sept 28-29 2006, Dublin,
Ireland

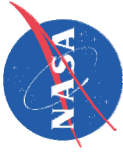
“Jet Measurements for Development of Jet Noise Prediction Tools”
James Bridges, NASA Glenn Research Center

The primary focus of my presentation is the development of the jet noise prediction code JeNo with most examples coming from the experimental work that drove the theoretical development and validation. JeNo is a statistical jet noise prediction code, based upon the Lilley acoustic analogy. Our approach uses time-average 2-D or 3-D mean and turbulent statistics of the flow as input. The output is source distributions and spectral directivity.

NASA has been investing in development of statistical jet noise prediction tools because these seem to fit the middle ground that allows enough flexibility and fidelity for jet noise source diagnostics while having reasonable computational requirements. These tools rely on Reynolds-averaged Navier-Stokes (RANS) computational fluid dynamics (CFD) solutions as input for computing far-field spectral directivity using an acoustic analogy. There are many ways acoustic analogies can be created, each with a series of assumptions and models, many often taken unknowingly. And the resulting prediction can be easily reverse-engineered by altering the models contained within. However, only an approach which is mathematically sound, with assumptions validated and modeled quantities checked against direct measurement will give consistently correct answers. Many quantities are modeled in acoustic analogies precisely because they have been impossible to measure or calculate, making this requirement a difficult task.

The NASA team has spent considerable effort identifying all the assumptions and models used to take the Navier-Stokes equations to the point of a statistical calculation via an acoustic analogy very similar to that proposed by Lilley. Assumptions have been identified and experiments have been developed to test these assumptions. In some cases this has resulted in assumptions being changed. Beginning with the CFD used as input to the acoustic analogy, models for turbulence closure used in RANS CFD codes have been explored and compared against measurements of mean and rms velocity statistics over a range of jet speeds and temperatures. Models for flow parameters used in the acoustic analogy, most notably the space-time correlations of velocity, have been compared against direct measurements, and modified to better fit the observed data. These measurements have been extremely challenging for hot, high speed jets, and represent a sizeable investment in instrumentation development. As an intermediate check that the analysis is predicting the physics intended, phased arrays have been employed to measure source distributions for a wide range of jet cases. And finally, careful far-field spectral directivity measurements have been taken for final validation of the prediction code. Examples of each of these experimental efforts will be presented.

The main result of these efforts is a noise prediction code, named JeNo, which is in mid-development. JeNo is able to consistently predict spectral directivity, including aft angle directivity, for subsonic cold jets of most geometries. Current development on JeNo is focused on extending its capability to hot jets, requiring inclusion of a previously neglected second source associated with thermal fluctuations. A secondary result of the intensive experimentation is the archiving of various flow statistics applicable to other acoustic analogies and to development of time-resolved prediction methods. These will be of lasting value as we look ahead at future challenges to the aeroacoustic experimentalist.

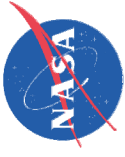


Jet Noise Diagnostics Supporting Statistical Noise Prediction Methods

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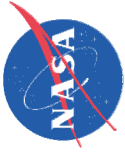
Presented at

10th CEAS-ASC Workshop 28/29 September, 2006
School of Engineering
Trinity College, Dublin



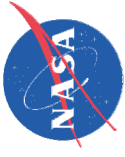
Acknowledgements

- Work contained herein was done in collaboration with
 - Mark Wernet (PIV)
 - Cliff Brown (Jet noise acoustics)
 - Sang Soo Lee (Phased arrays)
 - Abbas Khavaran (Jet noise prediction)
 - Nick Georgiadis (CFD)
 - Marv Goldstein (Aeroacoustic theory)
 - The staff of the AeroAcoustic Propulsion Lab at NASA Glenn
- With support of many other colleagues!



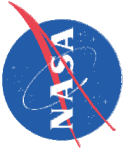
Outline

- Acoustic analogies and statistical prediction methods
- Assumptions and models in statistical jet noise codes
- Statistical quantities required
- Advanced instrumentation used
- Tests and results
 - Flow diagnostics
 - Acoustic diagnostics
 - Overall validation
 - Flight tests
- Prediction code status



Acoustic Analogies

- Classic exercise of applied mathematics
- Rearrange Navier-Stokes equations of motion as inhomogeneous wave equation to apply familiar methods of linear acoustics.
 - Need not be simple wave equation to be useful.
 - Many derivations/choices of variables ('analogies') possible.
- Ugly RHS to be treated as 'equivalent source'
 - Up to here equations are exact--no need for 'insight'
- Massive simplification/modeling done to RHS to make problem tractable.
 - Here's where the analyst needs experimental insight and data!
 - Statistical quantities which fall out are very difficult to measure!
 - This is where choice of analogy important.



Representative Derivation



Flow field: $p = p_0 + p'$, $v_i = \delta_{i1} U(x_2, x_3) + u_i$, $T = T_0(x_2, x_3) + T'$

Wave operator form: $L\pi' = \Gamma$, $\pi' \equiv (p/p_0)^{(1/\gamma)} - 1$

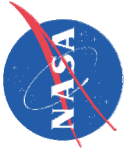
$$L\pi' \equiv \frac{D}{Dt} \left[\frac{D^2}{Dt^2} - \frac{\partial}{\partial x_i} c^2 \frac{\partial}{\partial x_i} \right] \pi' + 2c^2 \frac{\partial U}{\partial x_i} \frac{\partial^2 \pi'}{\partial x_i \partial x_1 \partial x_i}$$

$$\Gamma \equiv \frac{D}{Dt} \frac{\partial \zeta_i}{\partial x_i} - 2 \frac{\partial U}{\partial x_i} \frac{\partial \zeta_i}{\partial x_1}$$

$$\zeta_i \equiv \frac{\partial(u_i u_j)}{\partial x_j} + (\gamma \mathcal{R} T') \frac{\partial \pi'}{\partial x_i}$$



$$L\Pi \cong \frac{D}{Dt} \frac{\partial^2(u_i u_j)}{\partial x_i \partial x_j} - 2 \frac{\partial U}{\partial x_i} \frac{\partial^2(u_i u_j)}{\partial x_i \partial x_j \partial x_j}, \quad \Pi \cong \frac{p'}{p_0}$$



Representative Derivation, cont'd

Far-field spectral directivity:

$$\overline{p^2}(\bar{x}, \bar{y}, \omega) = \iint G^*(\bar{x}, \bar{y} - \bar{\xi}/2, \omega) G(\bar{x}, \bar{y} + \bar{\xi}/2, \omega) S(\bar{y}, \bar{\xi}, \tau) e^{i\omega\tau} d\tau d\bar{\xi}$$

$$\overline{S_{ijkl}(\bar{y}, \bar{\xi}, \tau)} = \overline{u_i u_j(\bar{y} - \bar{\xi}/2, t) u_k u_l(\bar{y} + \bar{\xi}/2, t + \tau)}(\bar{y})$$

$G(\bar{x}, \bar{y} + \bar{\xi}/2, \omega)$ is the Green's function for L.

For cold jets, the key quantity for modeling the source is the fourth order correlation matrix S_{ijkl} •



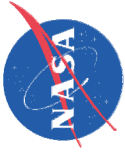
Assuming a compact source,



$$\overline{p^2}(\bar{x}, \bar{y}, \omega) = \iint |G|^2(\bar{x}, \bar{y}, \omega) S(\bar{y}, \bar{\xi}, \omega) d\bar{\xi}$$

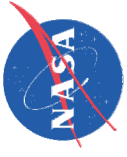


Model S, solve for the Green's function, and integrate. Simple!



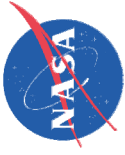
Key Assumptions/Models to be Checked

- Compact source assumption
- Model of fourth-order two-point space-time correlation of velocity
- Quasi-normal approximation
- Turbulence anisotropy model
- Time- and lengthscale models
- Accuracy of RANS CFD turbulence models
- Assumption of negligible enthalpic source
- Effect of heat on all above
- Effect of compressibility on all above



Experimental Technology

- Facilities
- Flow Diagnostics
- Acoustic Diagnostics
- High-Fidelity Simulated Flight
- Flight Tests

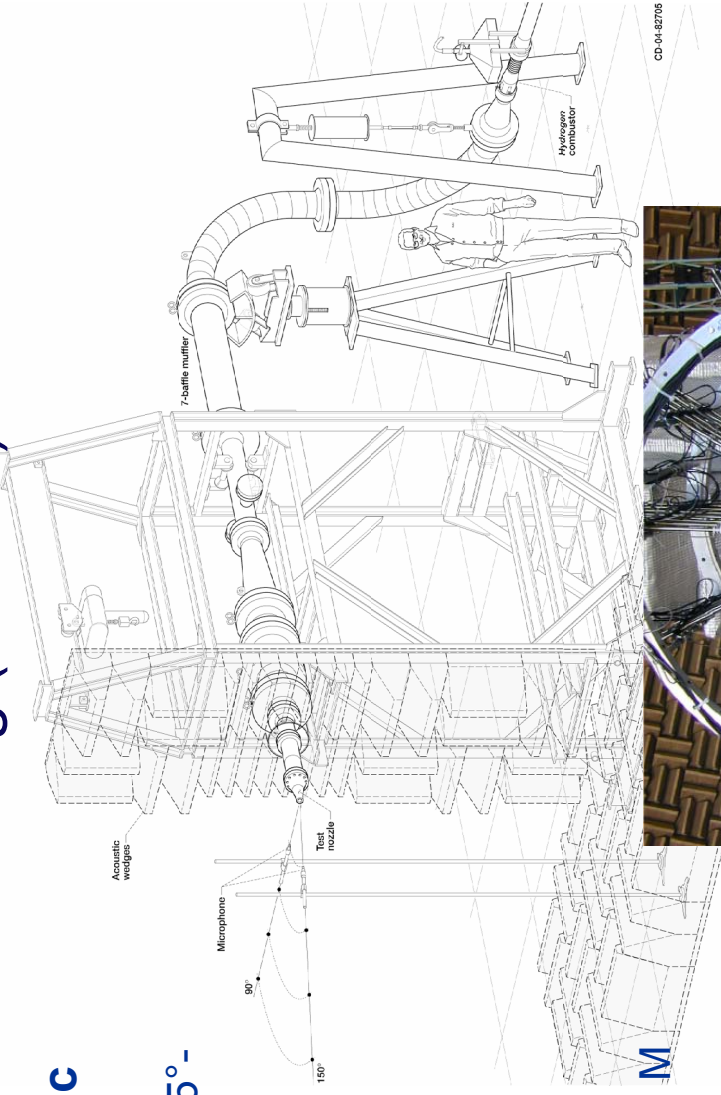


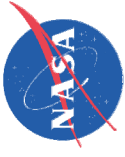
Glenn AeroAcoustics Propulsion Lab (AAPL)

Small Hot Jet Acoustic Rig (SHJAR)

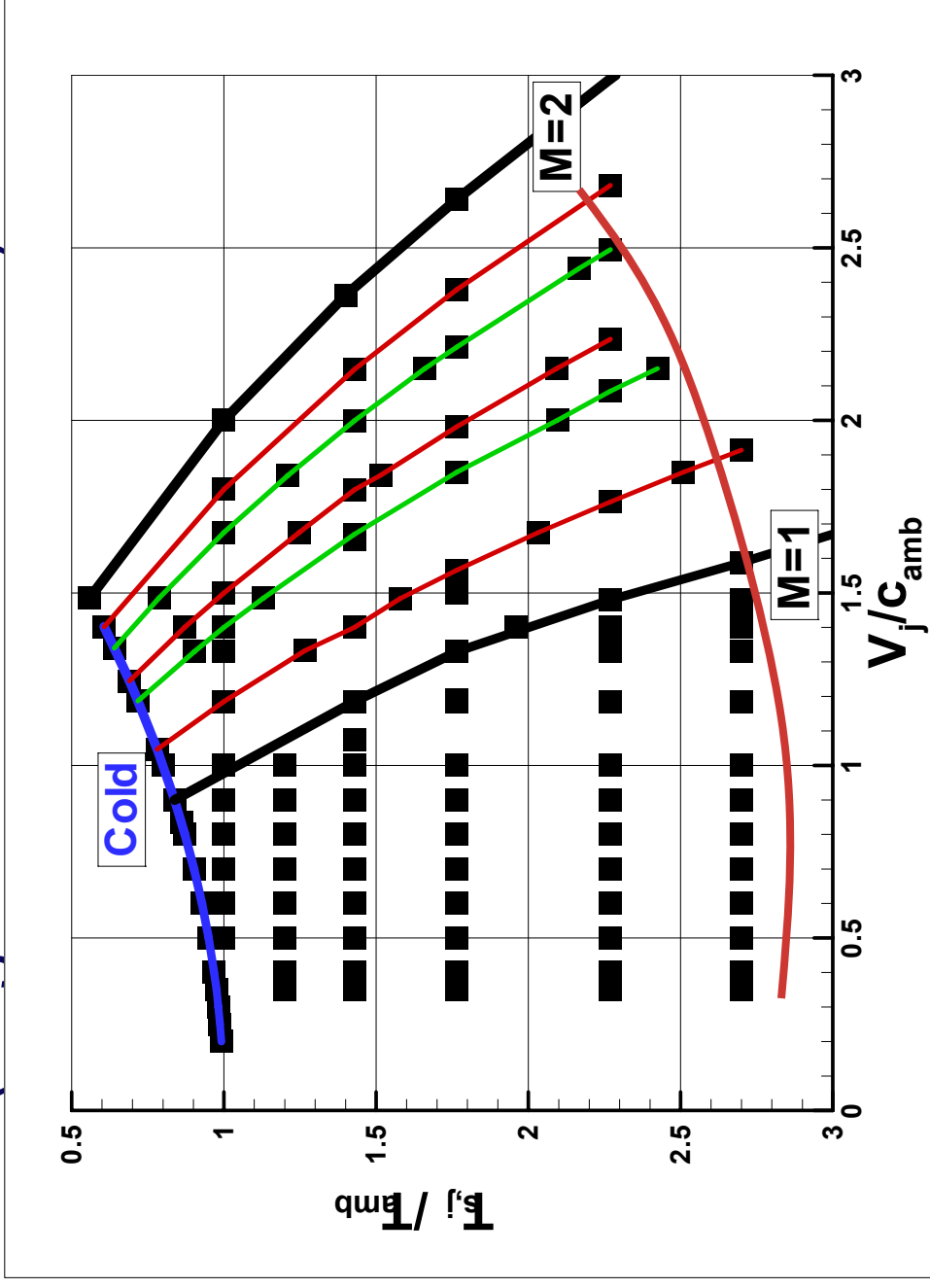
Low-cost operation for basic jet noise experiments

- 3m arc microphone array, 45° - 165° coverage
 - 200Hz cutoff
 - 50dB background
- Single stream jet
 - 2.5 kg/s up to 860K
 - 1–7 NPR
 - M_j , $T_j/T_{amb} \pm 0.2\%$
- Acoustically clean for $0.25 < M < 2$ with 50mm nozzle
- Full seeding capability for flow diagnostics.
- Ambient conditions monitored to within 0.2K, 1%RH
- Typical nozzle 25mm–75mm



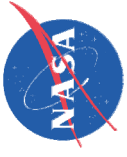


Flow+Sound Database Conditions (Augmented Tanna Matrix)



AFAPL-tr-76-65 (Lockheed-Georgia)

“The influence of temperature on shock-free supersonic jet noise”, JSV 39 1975

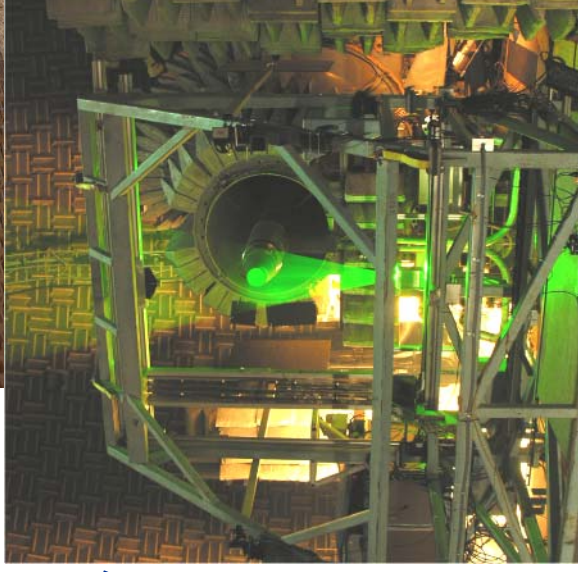
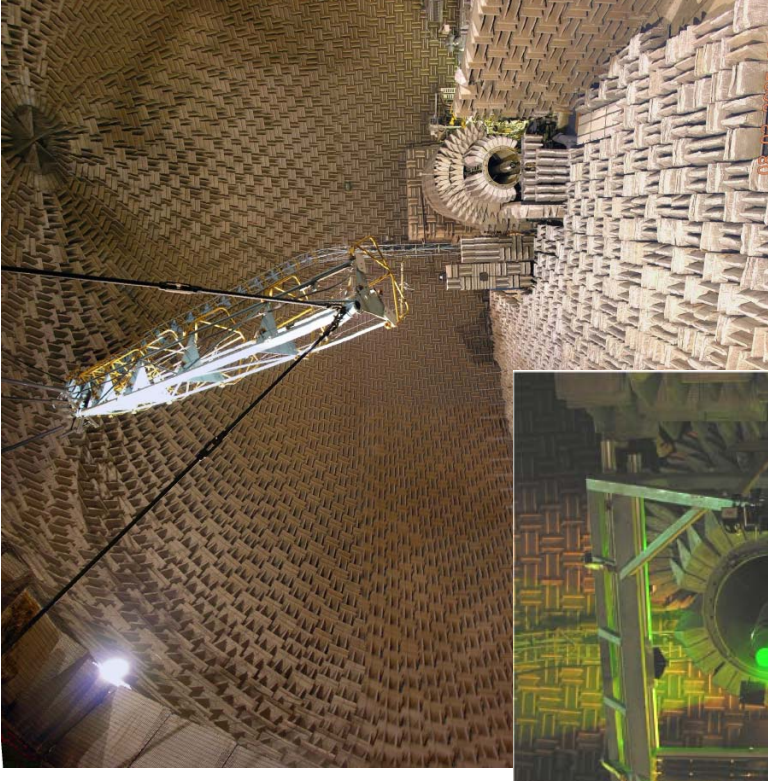


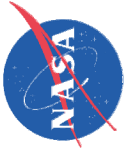
Glenn AeroAcoustics Propulsion Lab

(AAPL) Nozzle Acoustic Test Rig (NATR)

High-fidelity assessment of exhaust systems in flight with diagnostics

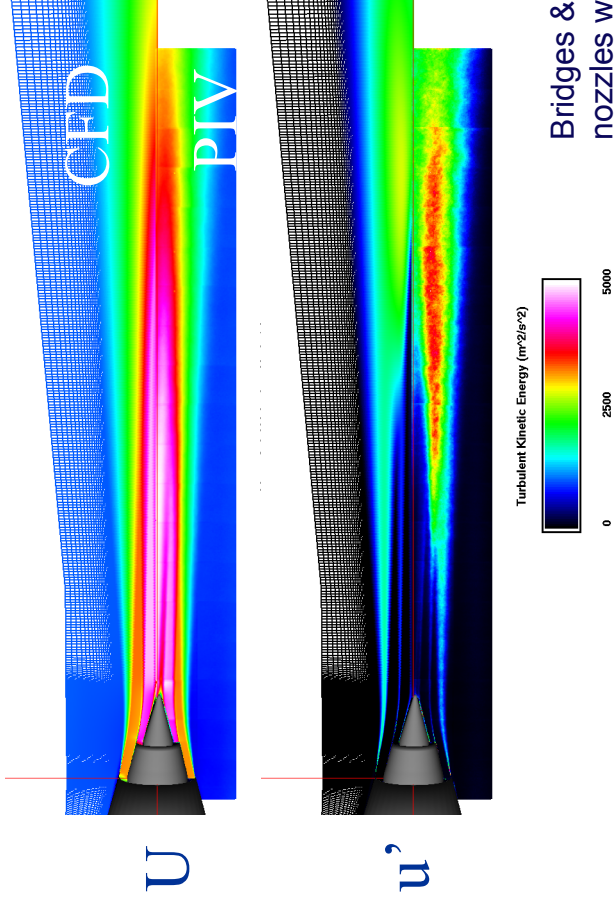
- 20m radius anechoic dome
- 14m arc microphone array, 45° -165° coverage.
- Dual flow engine simulator
 - Core stream 9 kg/s up to 850K
 - Fan stream 12 kg/s up to 390K
- Flight simulation $0 < M < 0.4$
- 200mm typical nozzle diameter
- Full seeding capability for flow diagnostics.



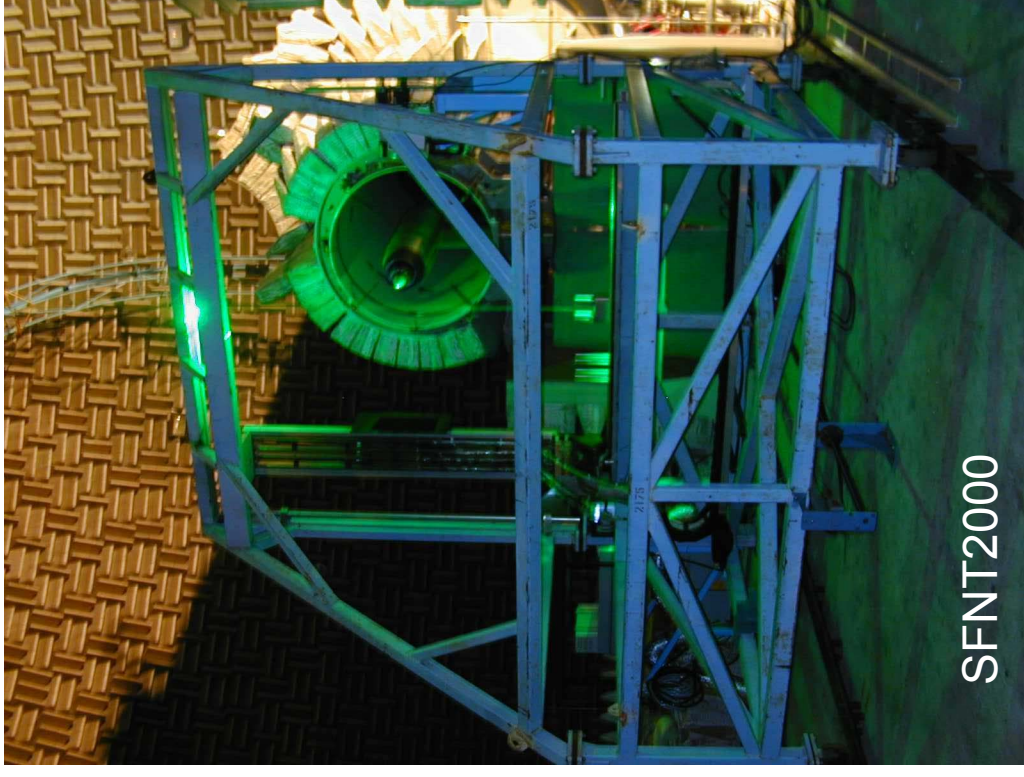


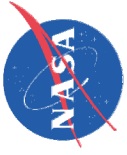
Flow Diagnostics

- Particle Image Velocimetry
 - Field of view
 - Seeding
 - Resolution
 - Stereo
 - Streamwise, Cross-stream

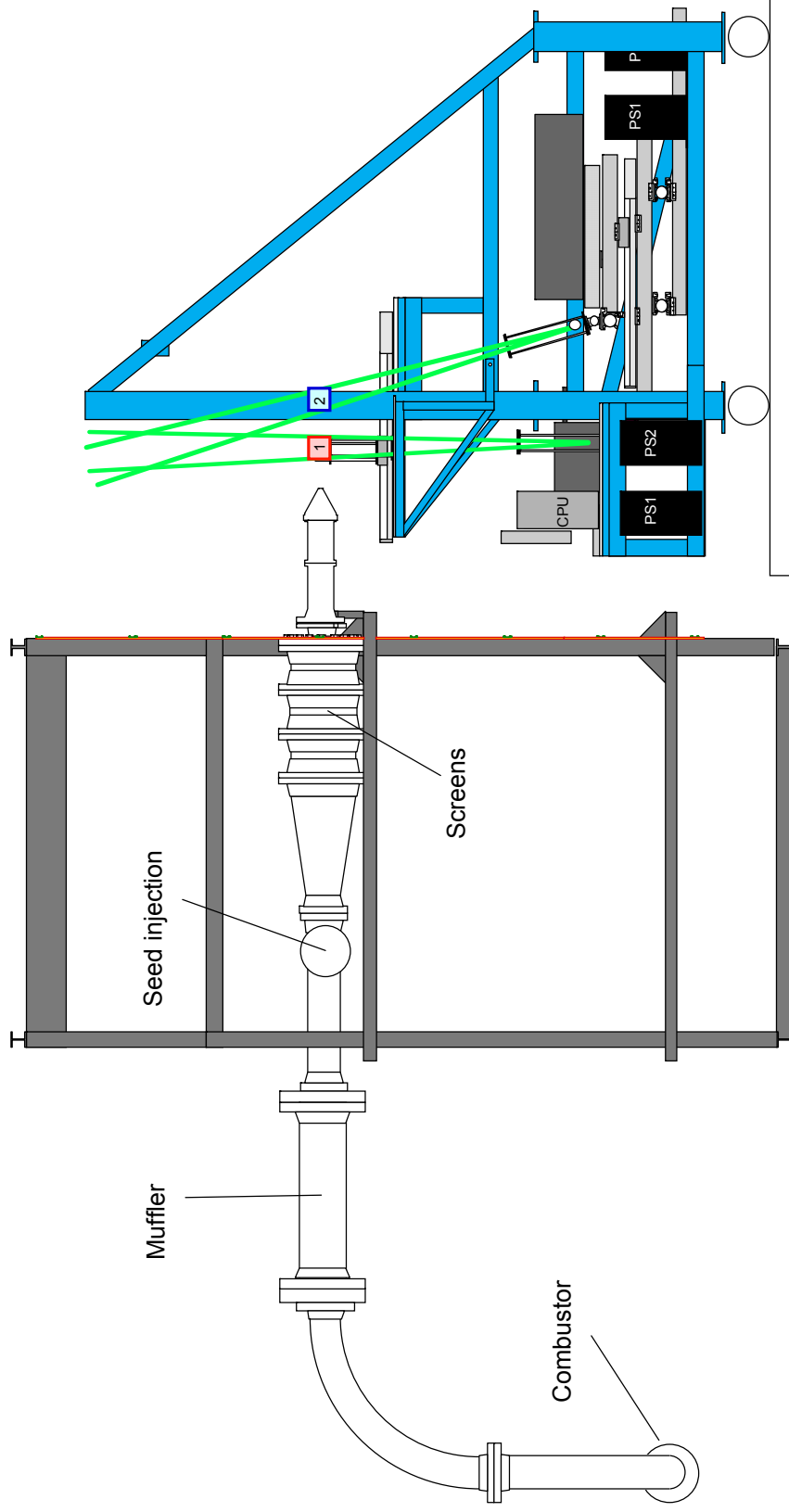


Bridges & Wernet, "Turbulence measurements of separate flow nozzles with mixing enhancement features," AIAA 2002-2484



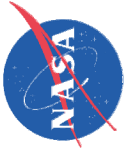


Dual PIV System Schematic Layout

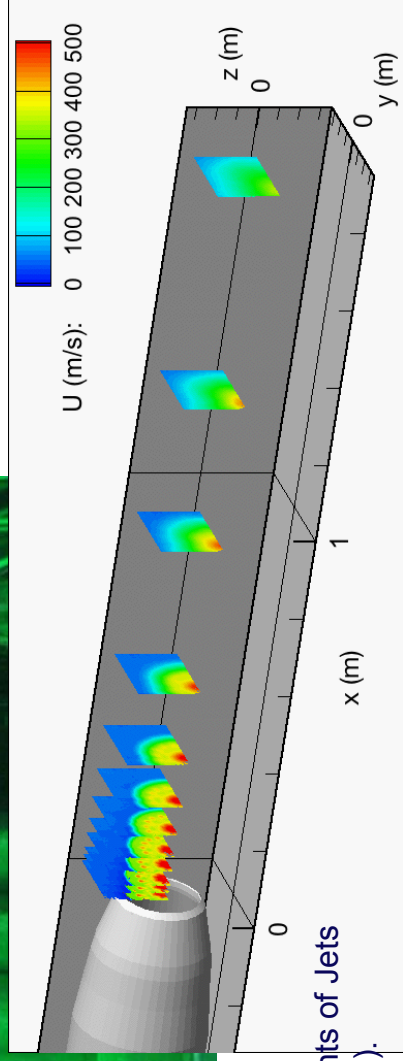
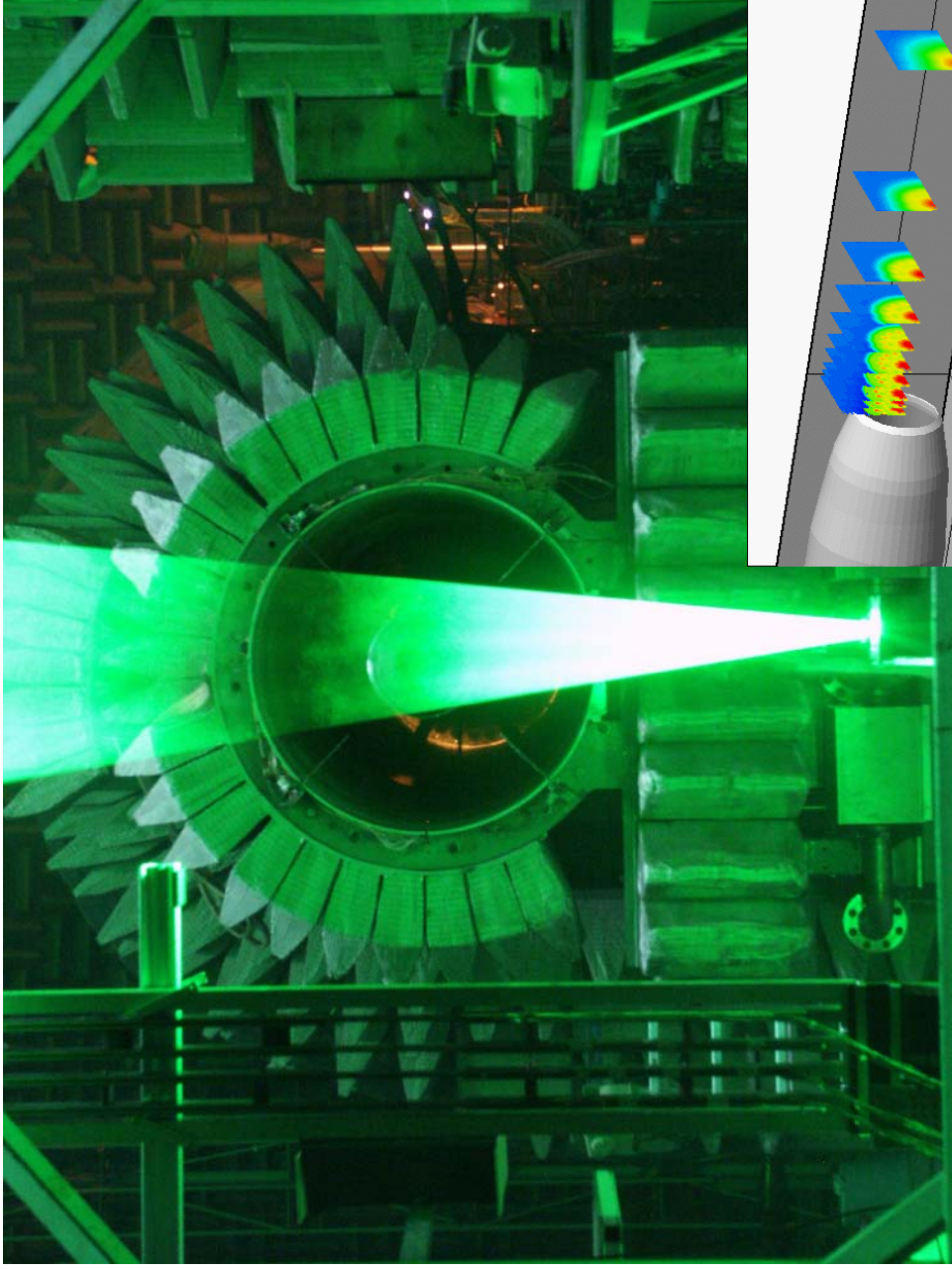


A person is seated at a workstation in a dark room, operating a laser scanning system. Two computer monitors display 3D point cloud data. A bright green laser beam is projected from the system onto a complex metal structure, illuminating it. The person's hand is on a keyboard. The scene is dimly lit, with the primary light source being the green laser.

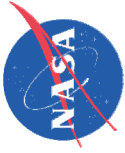




Cross-stream Stereo PIV



Bridges & Wernet, "Cross-Stream PIV Measurements of Jets with Internal Lobed Mixers," *AIAA 2004-2896* (2004).



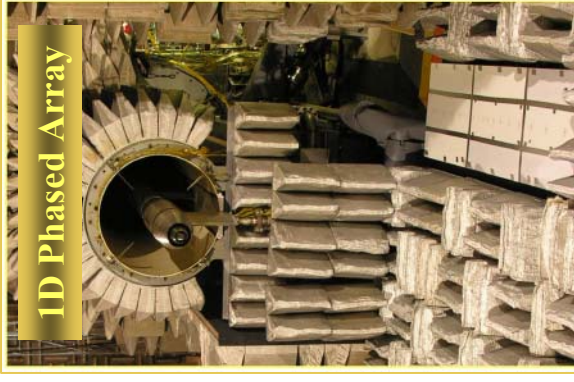
Acoustic Diagnostics



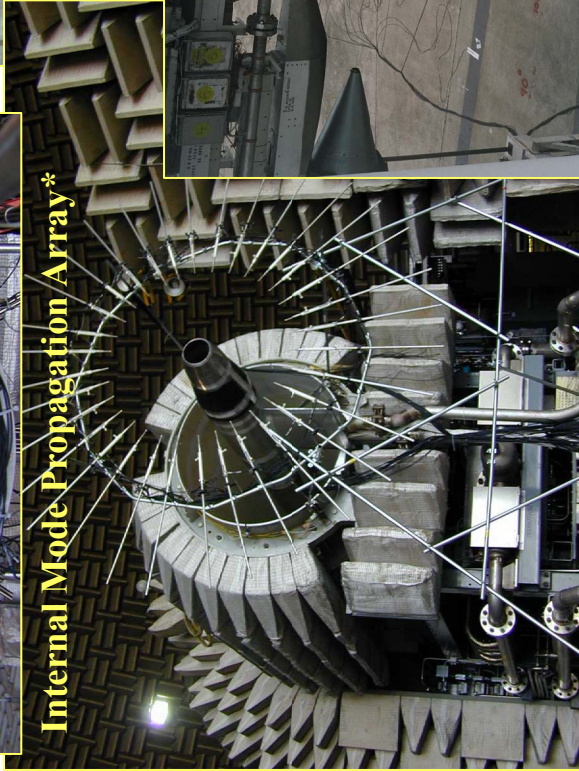
Near-Field Emission Array*



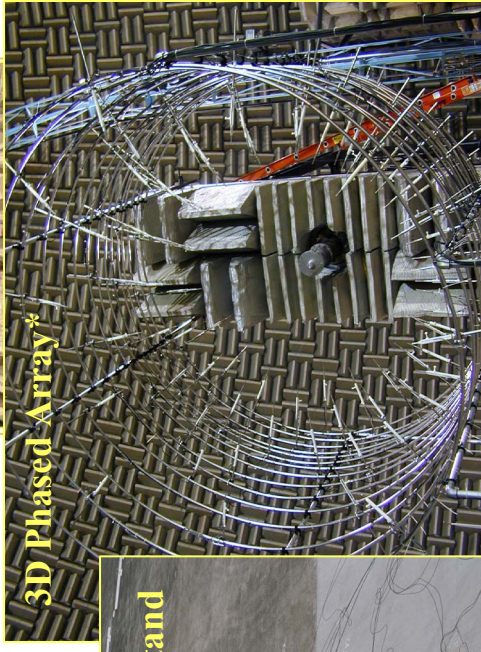
RRC Polar Correlation Array



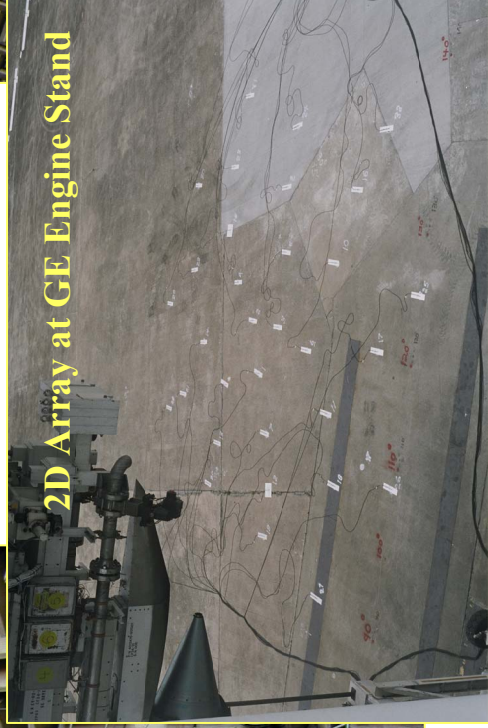
1D Phased Array



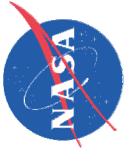
Internal Mode Propagation Array*



3D Phased Array*

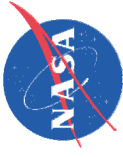


2D Array at GE Engine Stand



Validating Source Models

- Model of fourth-order two-point space-time correlation of velocity
 - Quasi-normal approximation
 - Turbulence anisotropy model
 - Model of second-order two-point space-time correlation of velocity
- Time- and lengthscales models
- Compact source assumption



Model of fourth-order two-point space-time correlation of velocity

- Quantity of interest is
- The fourth order space-time tensor is often approximated by

$$S_{ijkl}(\bar{y}, \bar{\xi}, \tau) = \overline{u_i u_j (\bar{y} - \bar{\xi}/2, t) u_k u_l (\bar{y} + \bar{\xi}/2, t + \tau)}$$

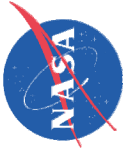
$$S_{ijkl} = \overline{u_i u_j u_k' u_l'} \approx \overline{u_i u_j u_k' u_l'} + \overline{u_i u_k' u_j u_l'} + \overline{u_i u_l' u_j u_k'}$$

to use second-order correlations which can be derived from simple turbulence models, such as those of Batchelor:

$$\overline{u_i u_j'} = R_{ij}(\bar{\xi}) g(\tau) = u_1^2 \left[\left(f + \frac{\xi f'}{2} \right) \delta_{ij} - \frac{\xi_i \xi_j f'}{2\xi} \right] g(\tau), \quad f(\bar{\xi}) = e^{-\pi \frac{\xi^2}{L^2}}$$

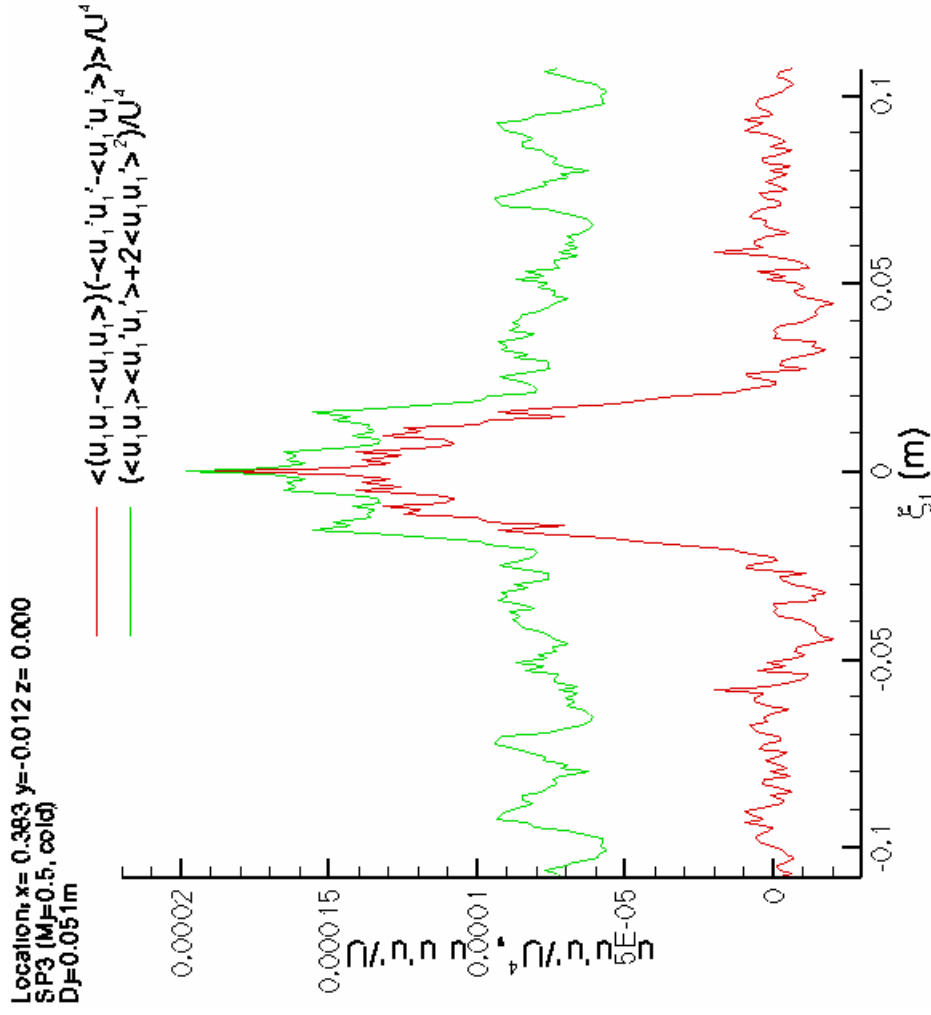
$$g(\tau) = e^{-\pi \frac{\tau^2}{T^2}}$$

- Questions:
 - Is the quasi-normal approximation valid?
 - Are the second-order correlation models for R_{ij} valid?
 - What are the model coefficients (lengthscale L and timescale T)?

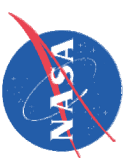


Quasi-normal approximation

- Compare $\langle uuu'u' \rangle$ to $\langle uu \rangle \langle u'u' \rangle$



- Approximation not valid except near $\xi = 0$.
- Must remove $\langle uu \rangle$ from each first!

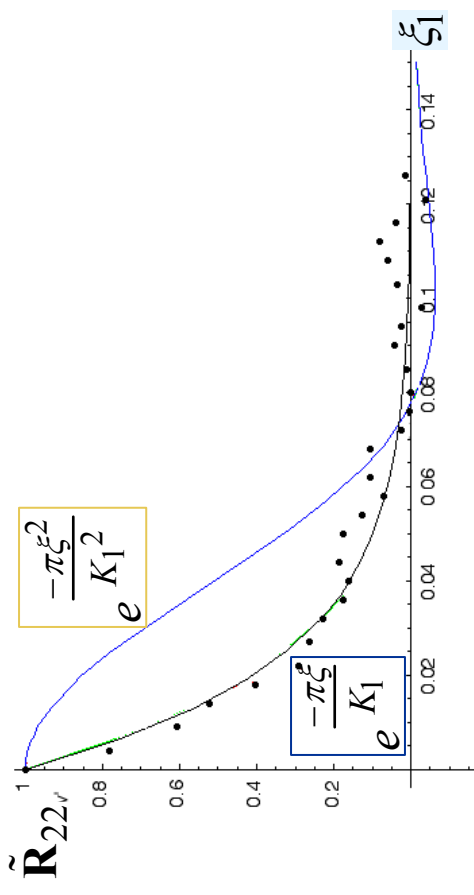
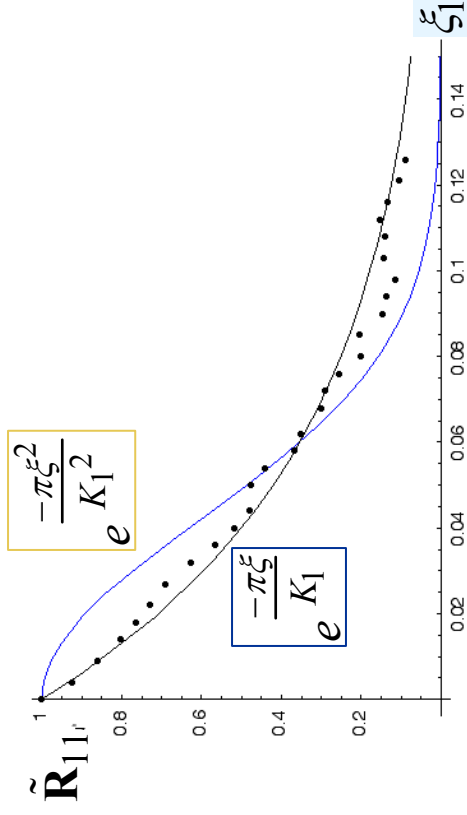


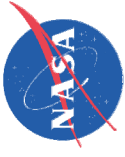
Axisymmetric Turbulence Model for Second Order Correlations

- An axisymmetric turbulence model can be constructed which has an exponential core with two lengthscale parameters K_1 , K_2

$$Q_1 = -\frac{u_1^2}{2} e^{-\pi \sqrt{\left(\frac{\xi_1^2}{K_1^2} + \frac{\xi_2^2 + \xi_3^2}{K_2^2} \right)}}; \quad \Delta = \frac{K_2}{K_1}$$

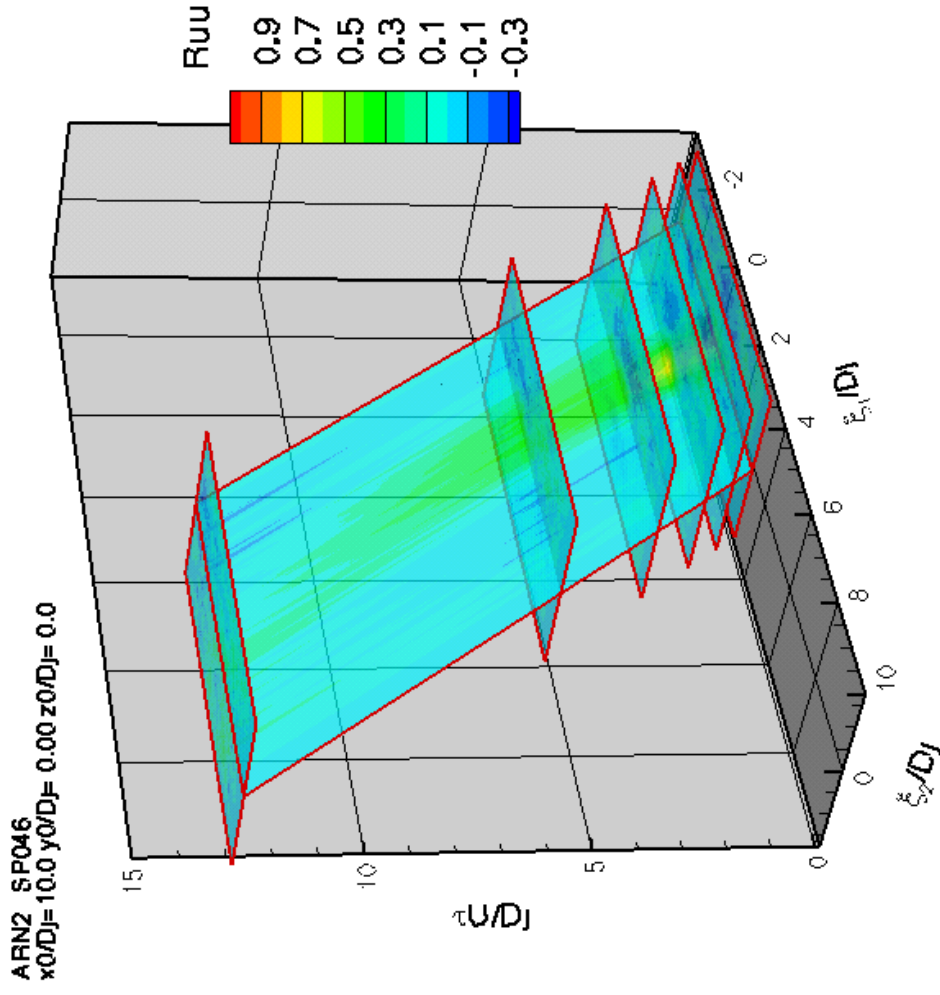
- We choose single-power exponent form because of superior fit to data:

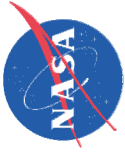




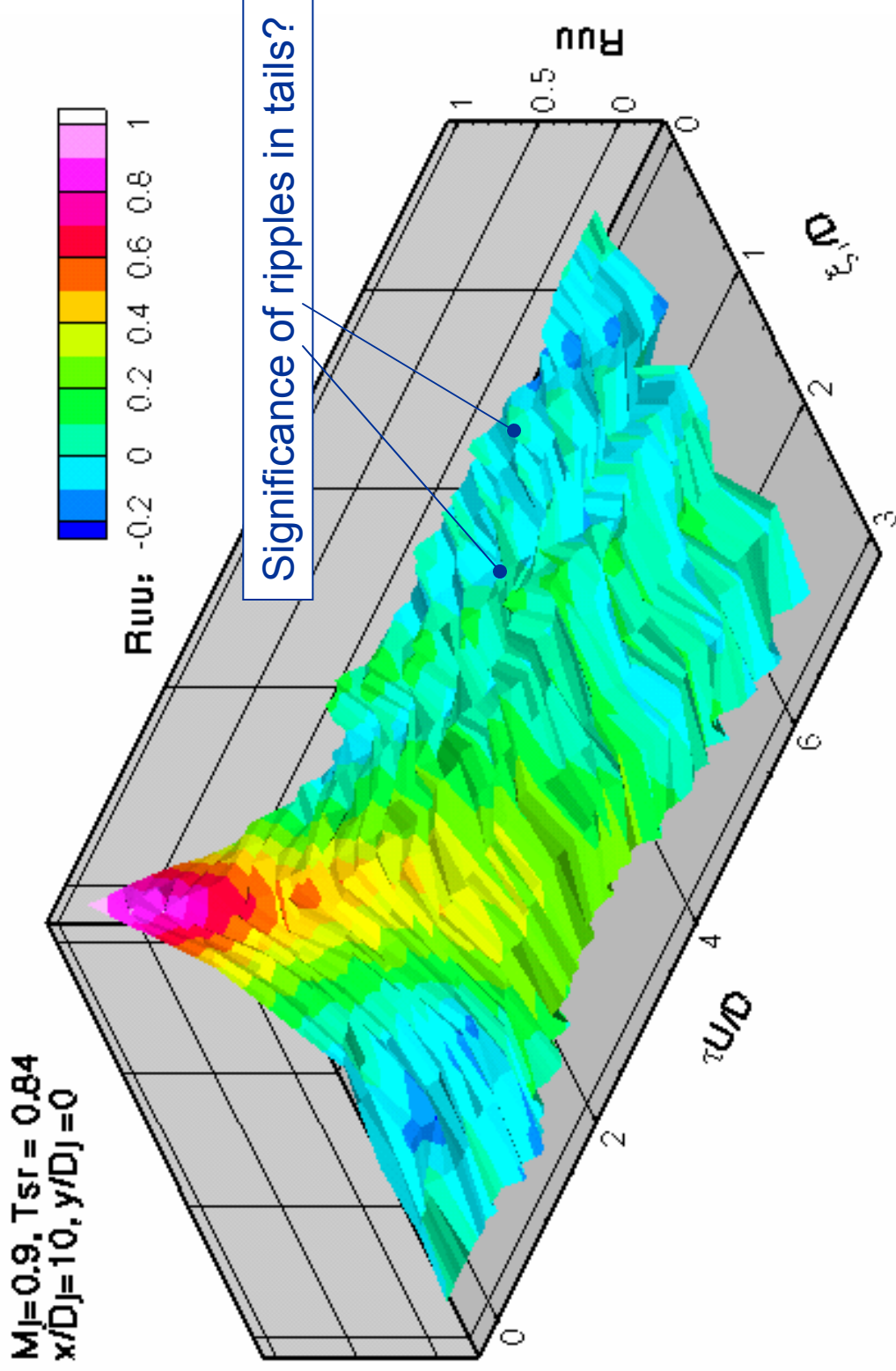
Space-Time Correlations of Velocity Dataset

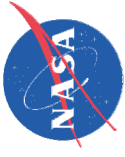
- Data acquired at 5 axial locations
 - $x/D_j = 2, 6, 10, 16, 22$
- Data processed for 9 radial locations
 - $y/D_j = 0, \pm 0.25, \pm 0.5, \pm 0.75, \pm 1$
- Data acquired at 6 space-time separations, anticipating convection velocities.
- Dataset yields R_{uu} , R_{vv} , $R_{u'}$ for ξ_1/D_j , ξ_2/D_j , $\tau U/D_j$
- Can be mined for turbulence models, convection velocity, lengthscales, and timescales.





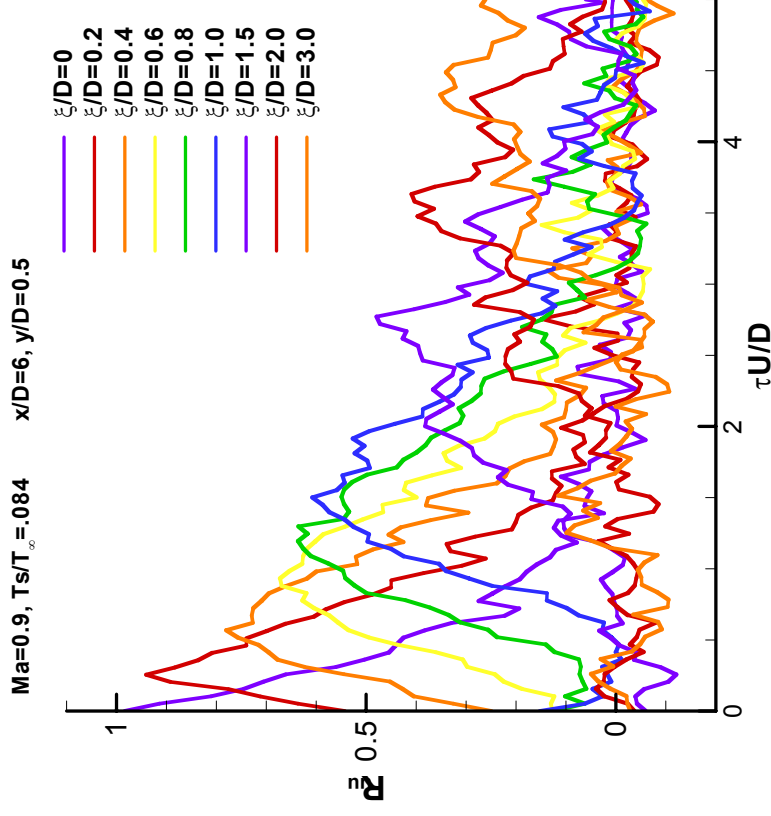
Interpolated 2nd order, space-time correlation

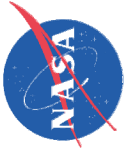




Extracting Temporal Correlations

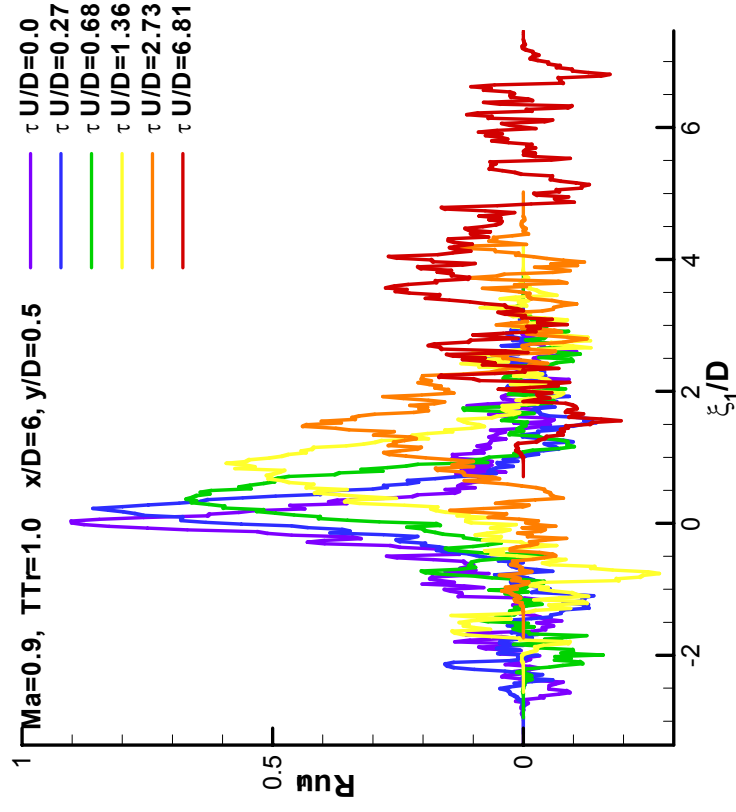
- Mining the $R_{uu}(\xi, \tau)$ for $\xi_2 = 0$, at different ξ_1 produces ‘standard’ (hot-wire) temporal correlations.
- $Ma = 0.9$ shown at $x/D_j = 6$, $y/D_j = 0.5$ for $T_j/T_\infty = 0.84$.
- Timescale τ_ω derived from fitting peaks of R_{uu} to $\exp(-\tau/\tau_0)$

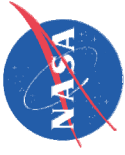




Extracting Spatial Correlations—Axial

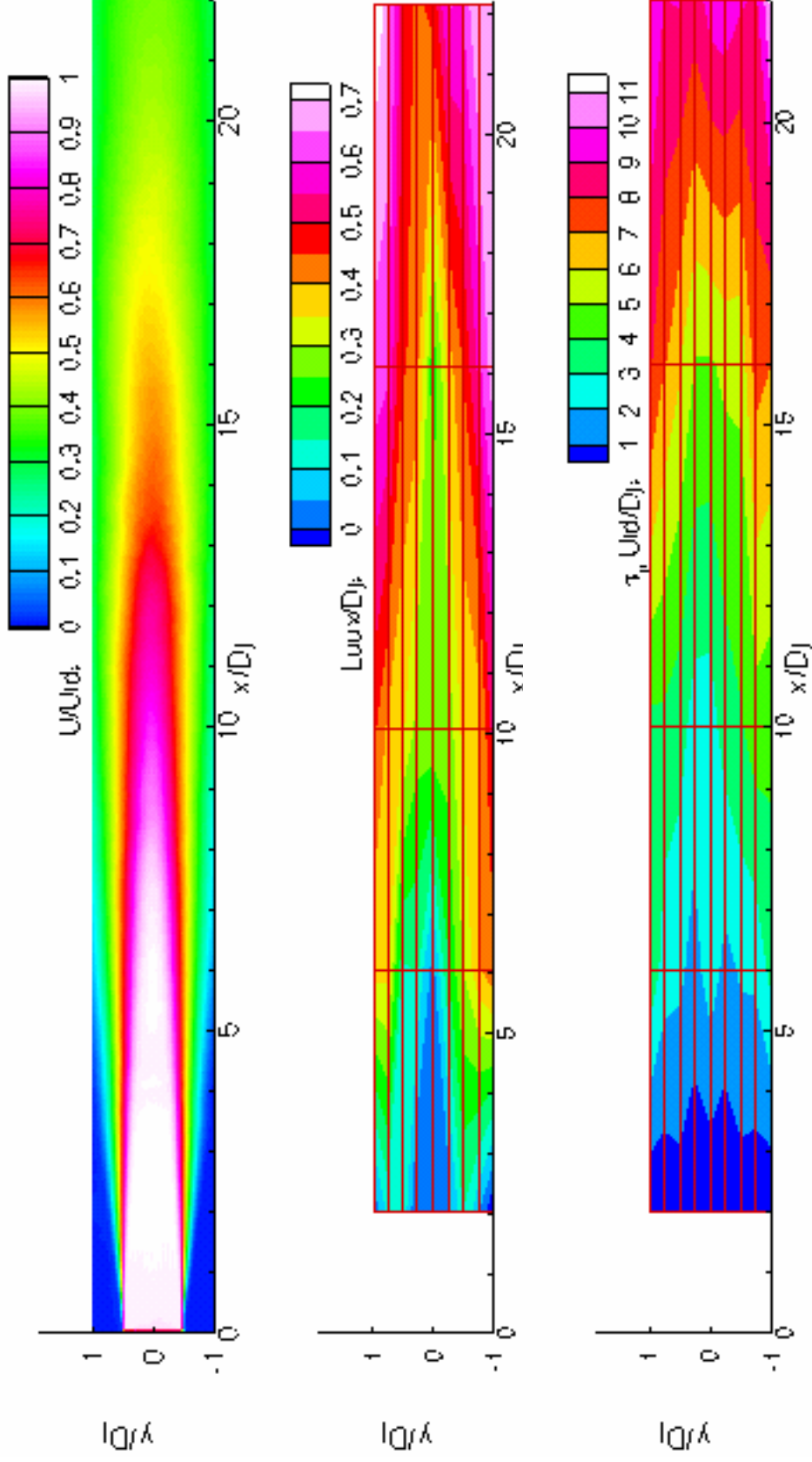
- Mining $R_{uu}(\xi, \tau)$ for $\xi_2 = 0$, at different τ produces spatial correlations.
- $Ma = 0.9$ shown at $x/D_j = 6$, $y/D_j = 0.5$ for $T_j/T_\infty = 0.84$.
- Lengthscale $L_{uu,x}$ obtained by integrating $R_{uu}(\xi_1; \xi_2=0, \tau=0)$ over ξ_1

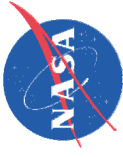




Parameters of Two-Point Correlation Models

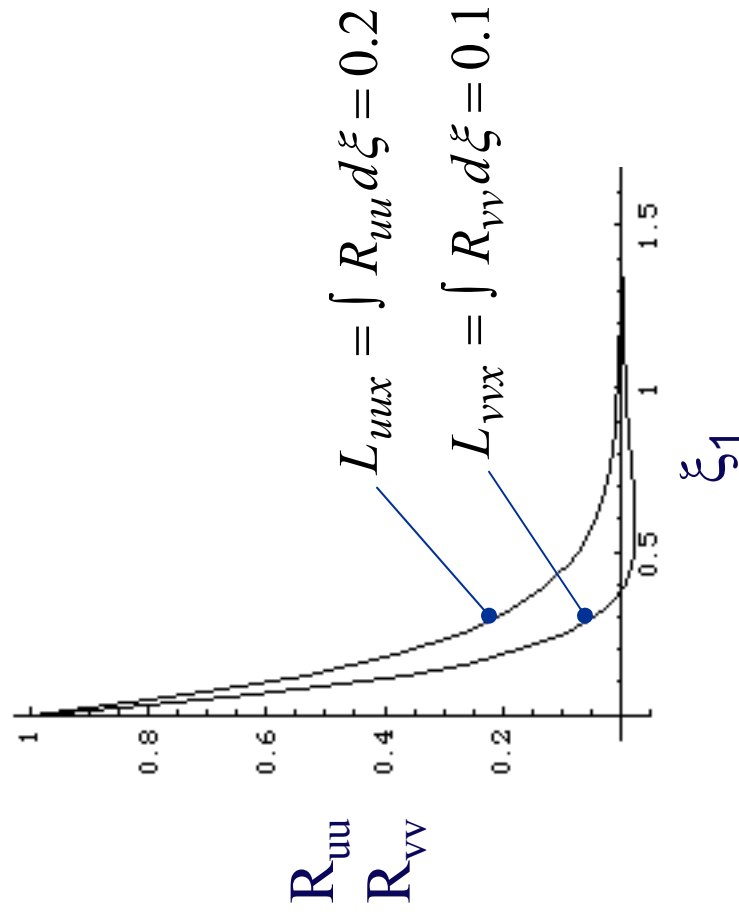
- Lengthscales, timescales

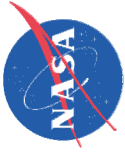




Compact Source Assumption

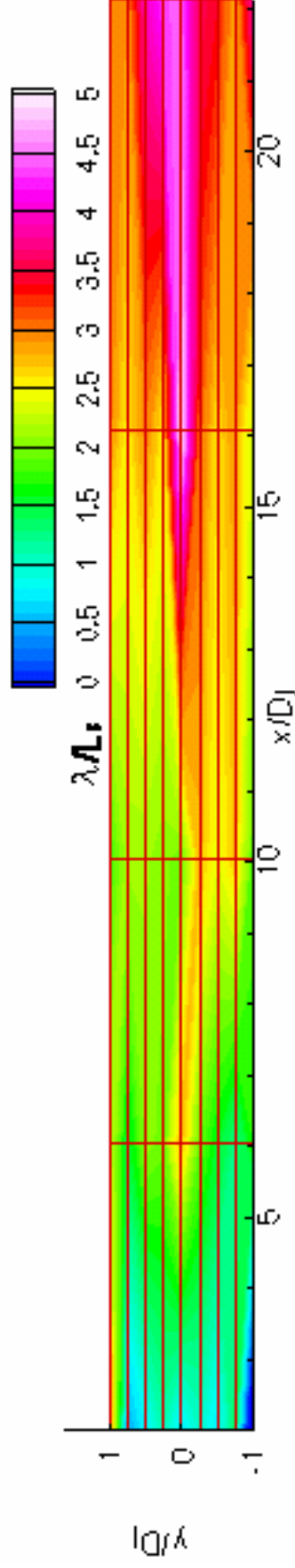
- Integral Lengthscale L_{uux} , proportional to length of significant correlation: **roughly factor of 5.**
- **Wavelength to correlation length $\lambda/L \sim \tau/(5L_{uux} \mathbf{M})$**

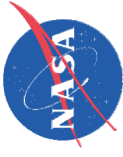




Source Compactness Estimation

- Wavelength to correlation length $\lambda/L \sim \tau/(5L_{\text{uux}} M)$
- $M=0.9$, cold
- λ/L in the range of 2 is not a compact source!

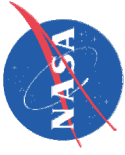




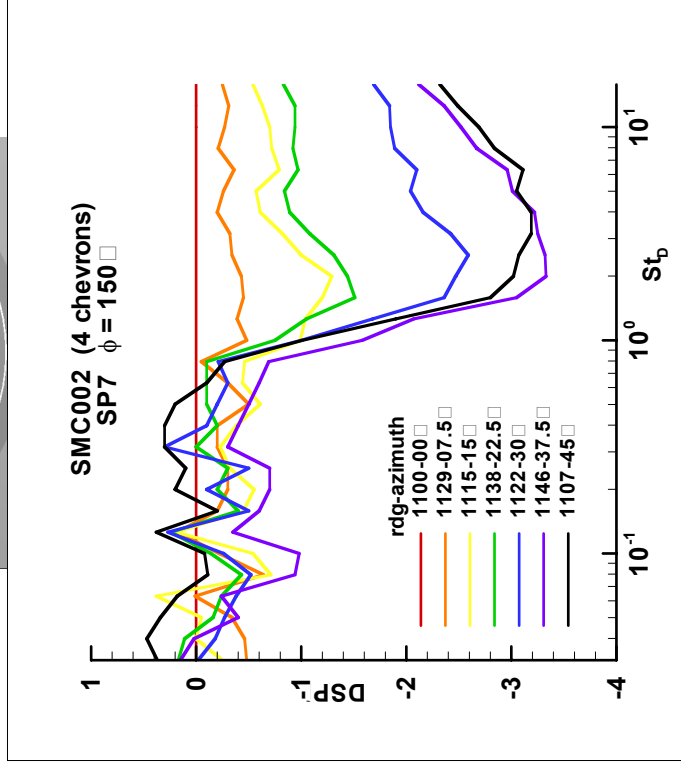
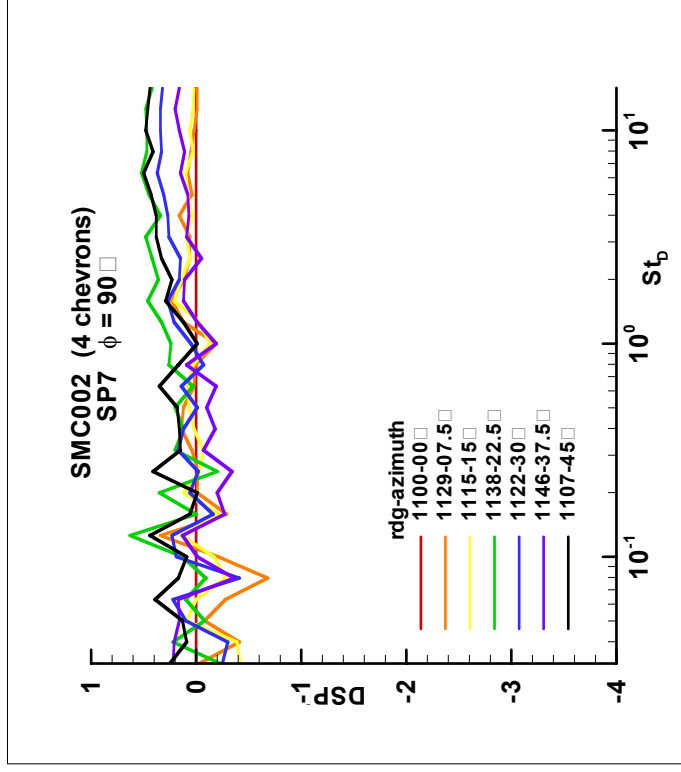
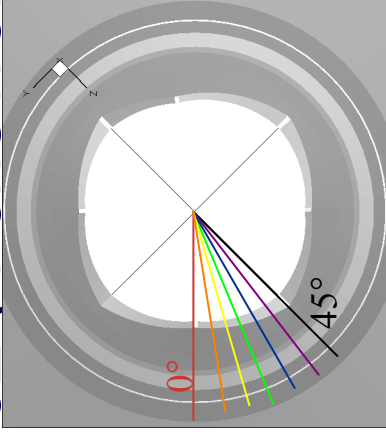
Validating Propagation

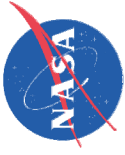
- Understanding impact of jet asymmetry
- When can integrands be simplified to produce 2.5-D approach?
- Measure azimuthal variation of sound field for jet plumes with various low-order azimuthal features.
- Used SMC-series chevron nozzles
 - SMC002 (4 chevrons)
 - SMC004 (5 chevrons)
 - SMC001 (6 chevrons)
- Tested over range of subsonic cold conditions, $0.5 < Ma < 0.9$
- Azimuthal variations accomplished by rotation of nozzle on rig.
 $f=0^\circ$ is along chevron tip.
- Plots of DSPL = SPL(f)-SPL(0°).



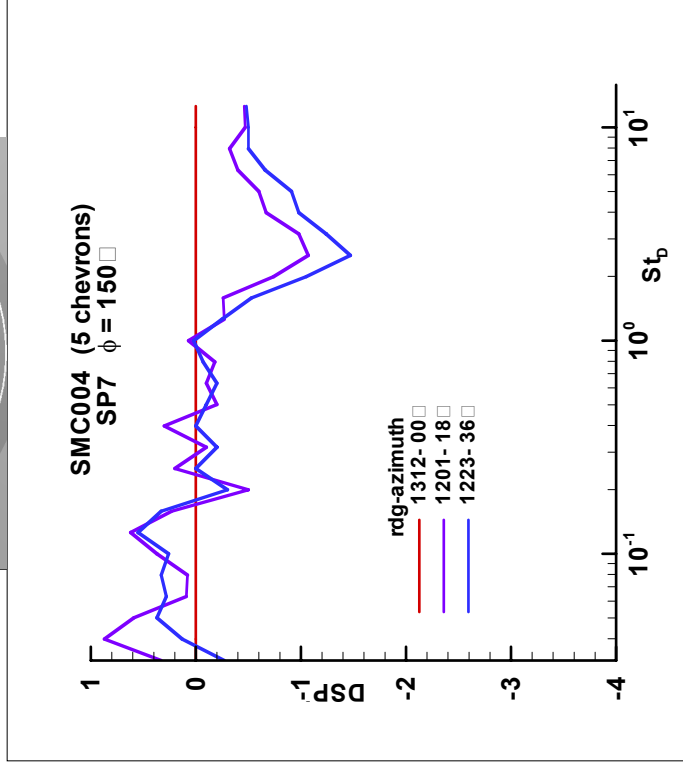
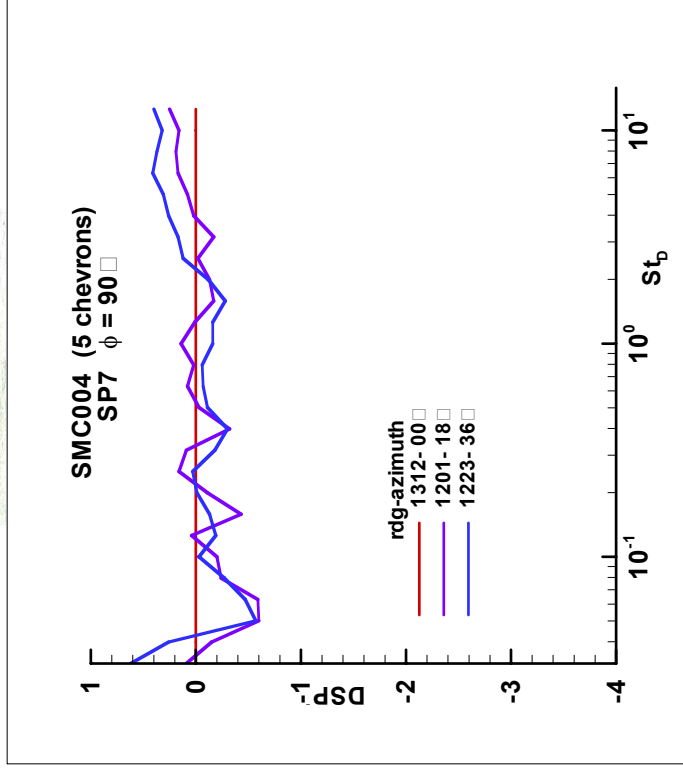
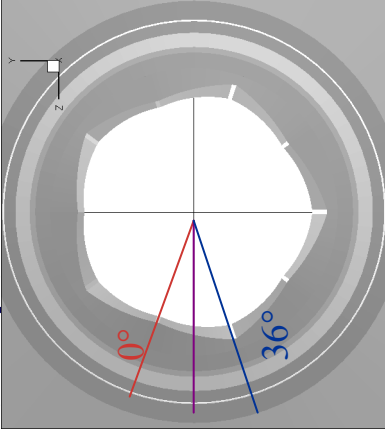


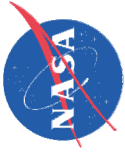
Setpoint 7 (Ma=0.9), SMC002 (4 chevrons)



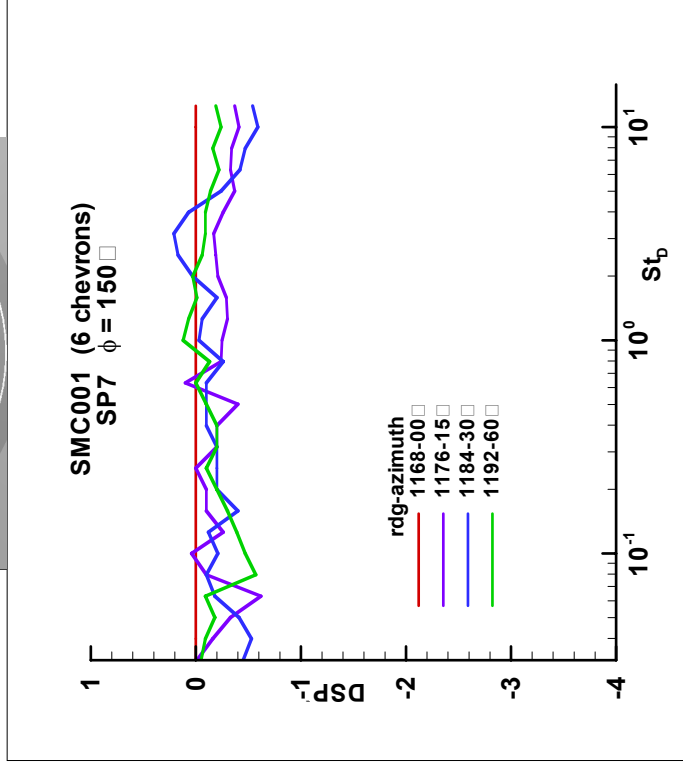
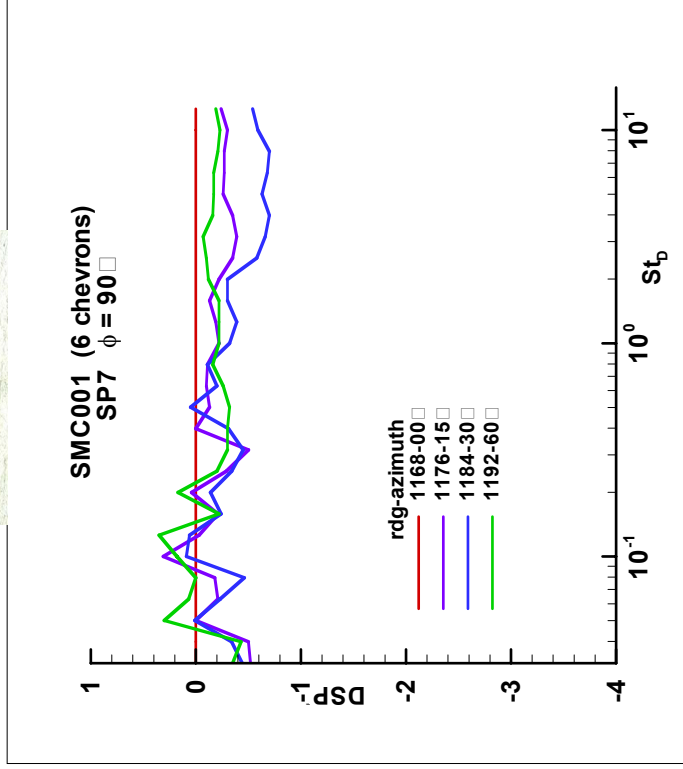
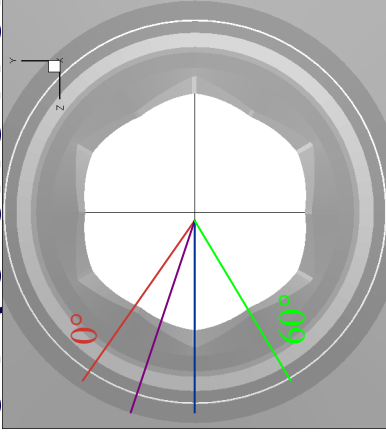


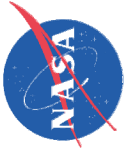
Setpoint 7 (Ma=0.9), SMC004 (5 chevrons)





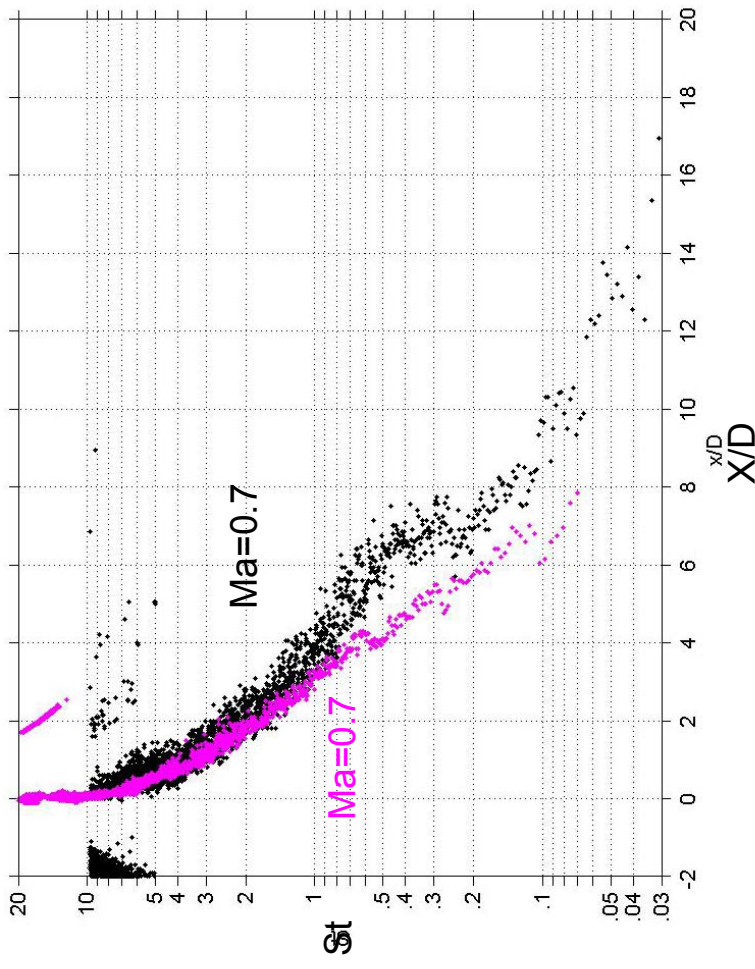
Setpoint 7 (Ma=0.9), SMC001 (6 chevrons)



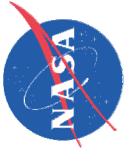


1D Phased Array

- One-dimensional, nonlinearly spaced phased array
- 8–24 flush mount microphones



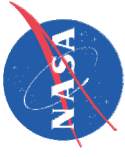
• Lee & Bridges, "Phased-array Measurements of Single Flow Hot Jets," AIAA 2005-2842



Jet Noise Understanding Mapping 3D Acoustic Source Density

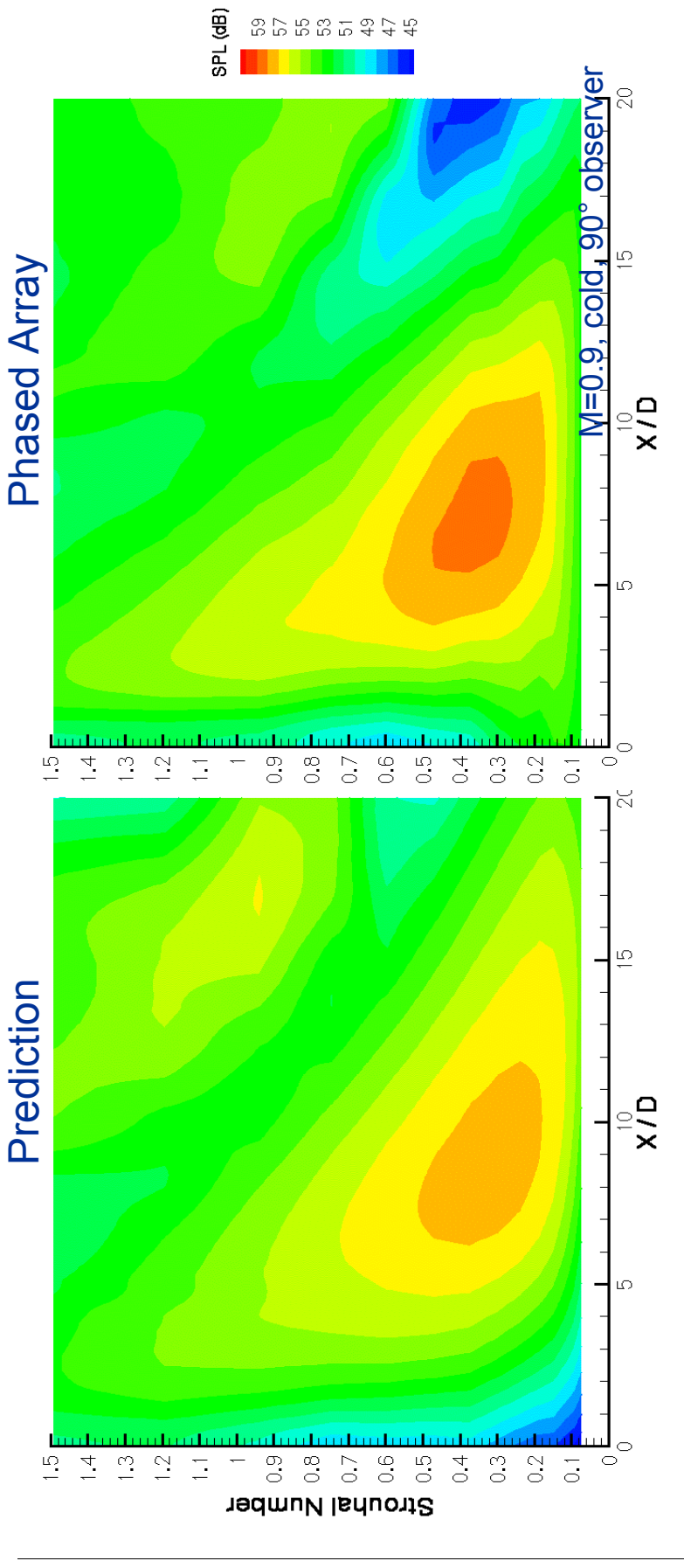
- GRC/SHJAR February 2004
- 80 microphone array
- Better point response function than Dougherty/Honeywell array.
- Results from conventional beamforming confusing--apparent sources located outside the jet at low frequencies!

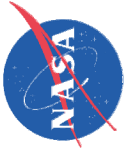




Jet Noise Source Density— Phased Array

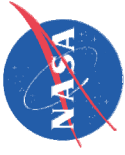
- Convolve predicted source distribution through phased array ‘filter’ for apples-apples comparison of acoustic source strength.





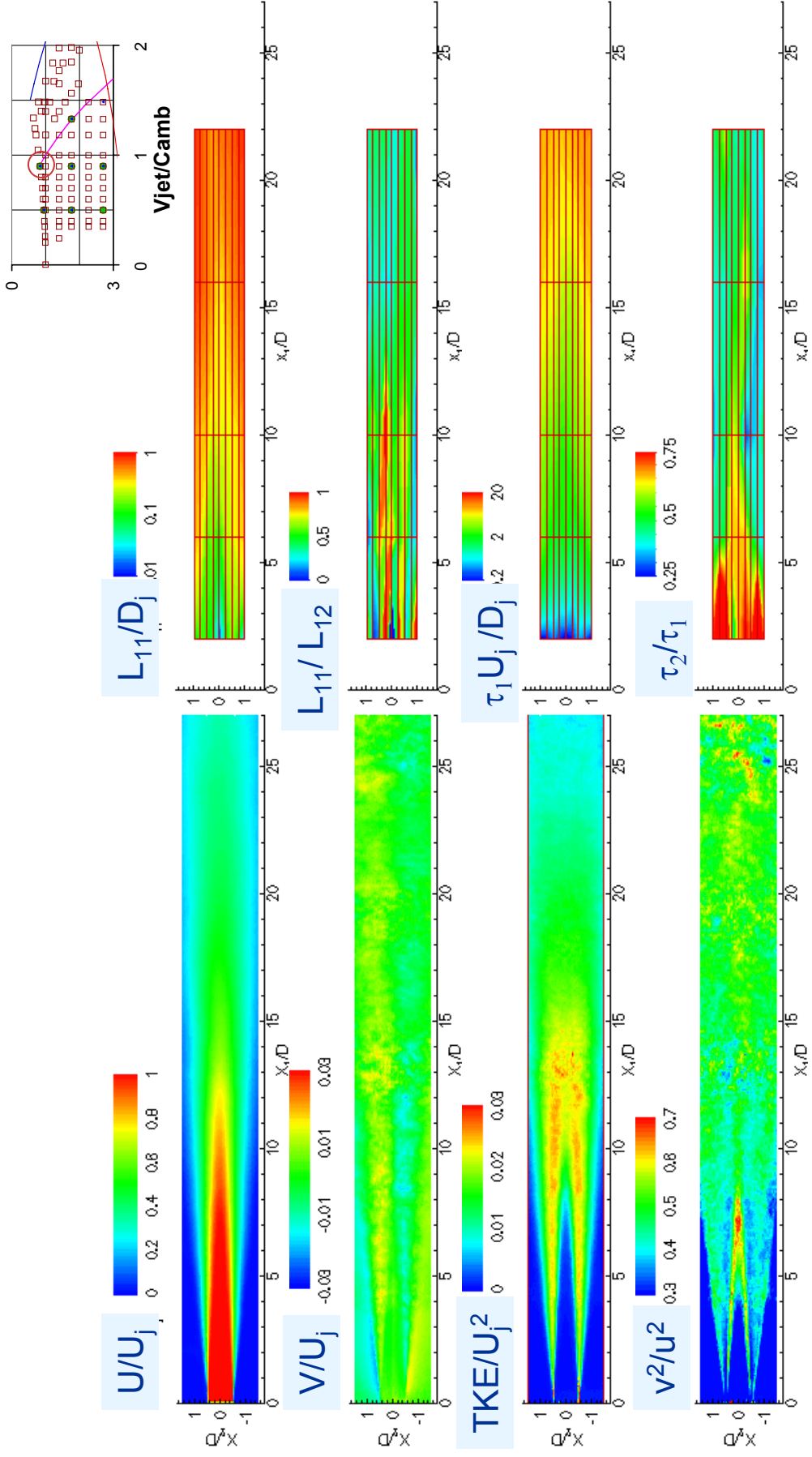
Validating RANS CFD

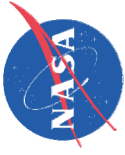
- Mean velocities, temperatures
- TKE, dissipation
- Range of M , T , geometries



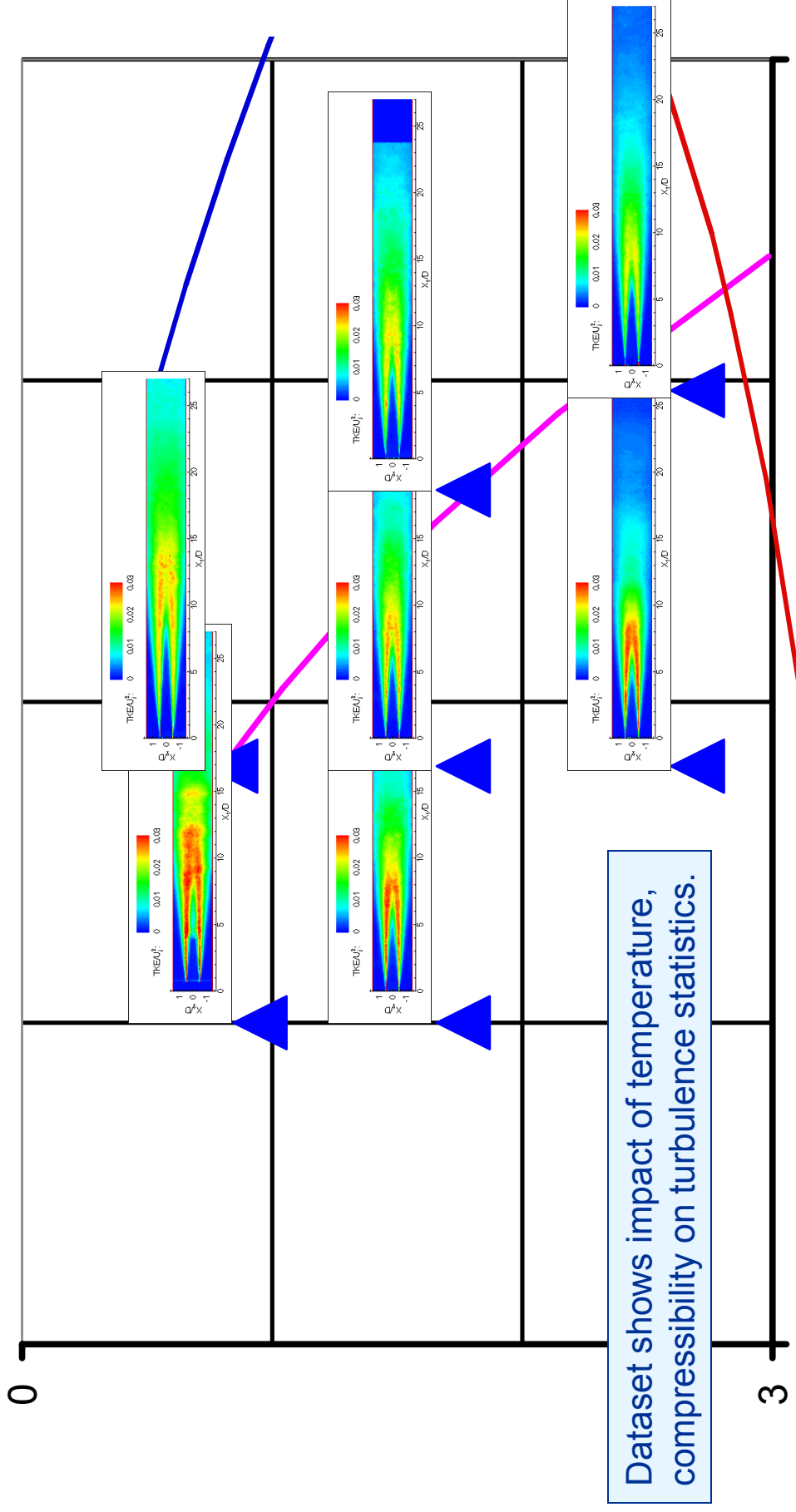
Baseline Data for CFD/CAA validation— Flow Stats

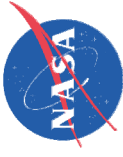
- Objective: Turbulent flow statistics for RANS validation





Baseline Data for CFD/CAA validation— Turbulent Kinetic Energy



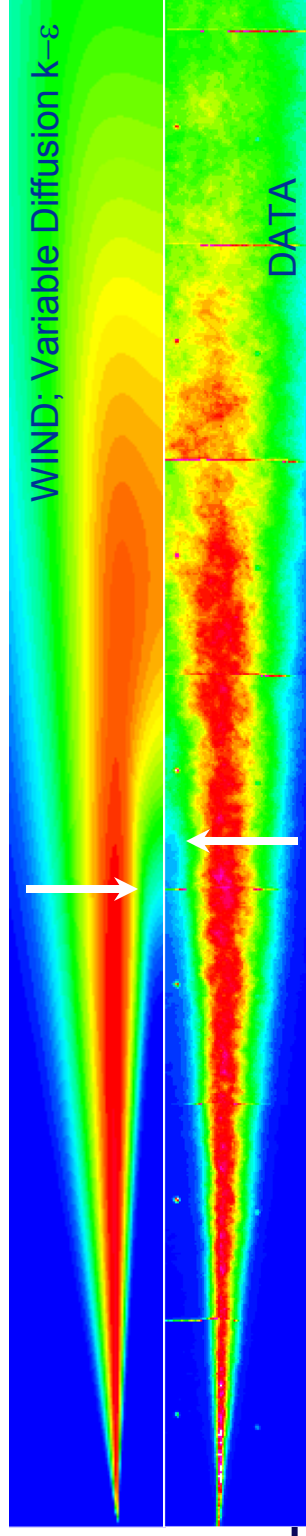
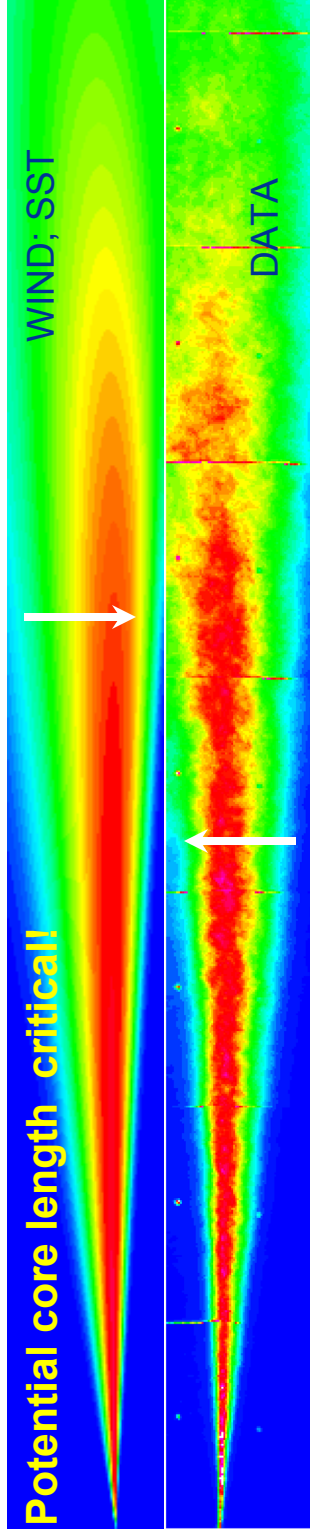


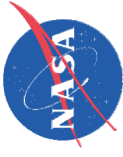
Evaluating RANS Turbulence Models for Jets

- Big problem for turbulence models in jets is that instabilities which drive turbulence change from 2D shear layer modes to 3D columnar modes.
- Models must be aware of geometry.
- Variable Diffusion k-eps model is one attempt.

Ma=0.9, cold

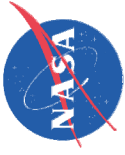
Turbulent Kinetic Energy





Final Validation of Spectral Directivity

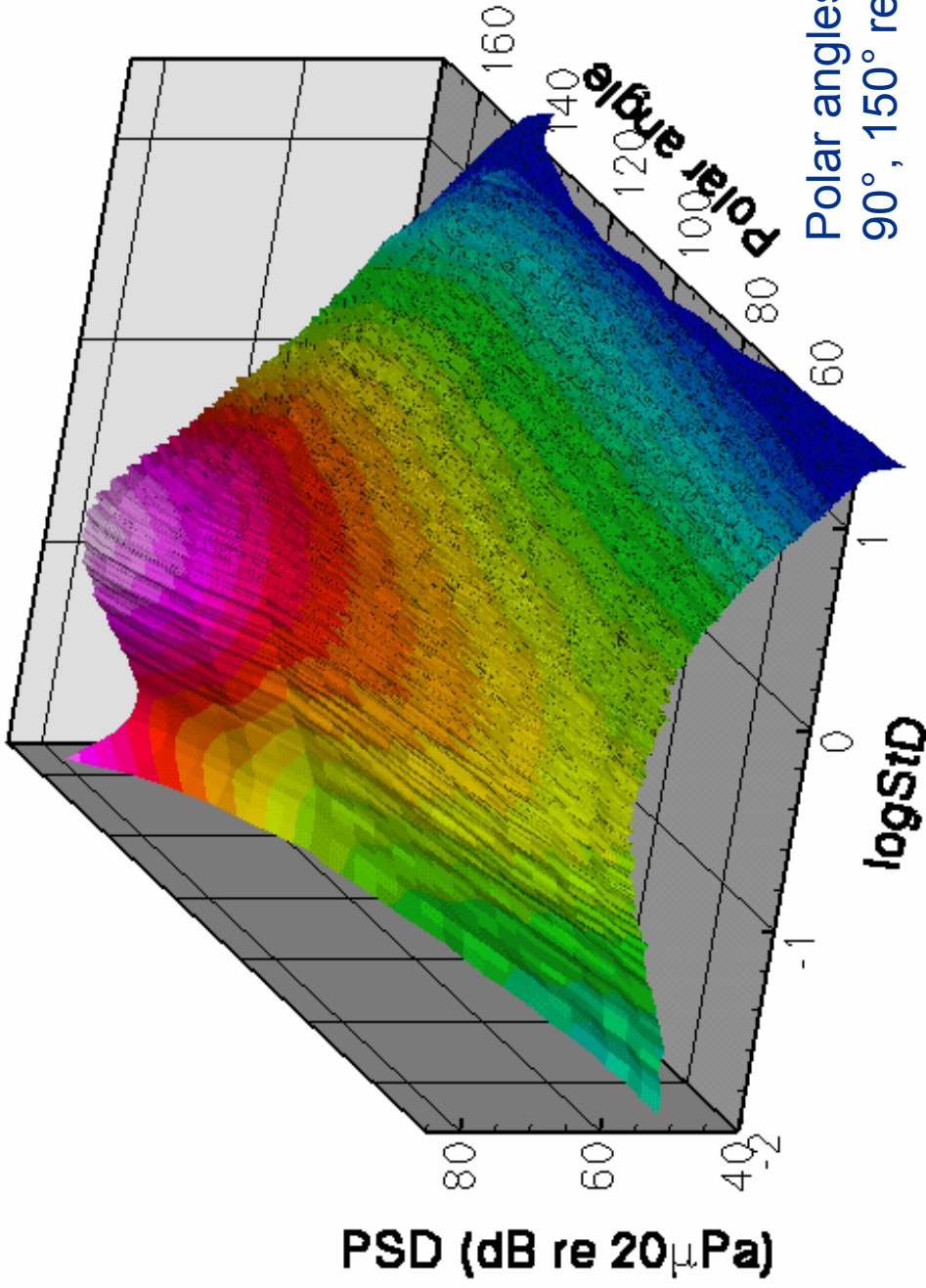
- Rig Dependence
- Error analysis
 - Uncertainty in measuring atmospheric conditions which feed the calculation of atmospheric attenuation
 - ~0.1dB, given the measurement uncertainty of 0.5K, 2% relative humidity
 - Uncertainty in setpoint
 - 0.17dB by holding 0.5% tolerance on the jet velocity
 - Uncertainty in spectral estimation
 - 0.33dB at low third-octave bands ($St < 0.05$).
 - Uncertainty in pistonphone calibrator B&K 4220
 - 0.15dB
 - Microphone holder reflection
 - 0.2dB from autocorrelation measurements
- But repeatable to within 0.2dB!



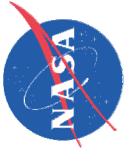
Jet Noise Spectral Directivity

Setpoint 7, $M_j=0.9$, $Tsr=0.84$
 $r/D_j=40$, lossless

PSD (dB re 20 μ Pa): 40 50 60 70 80



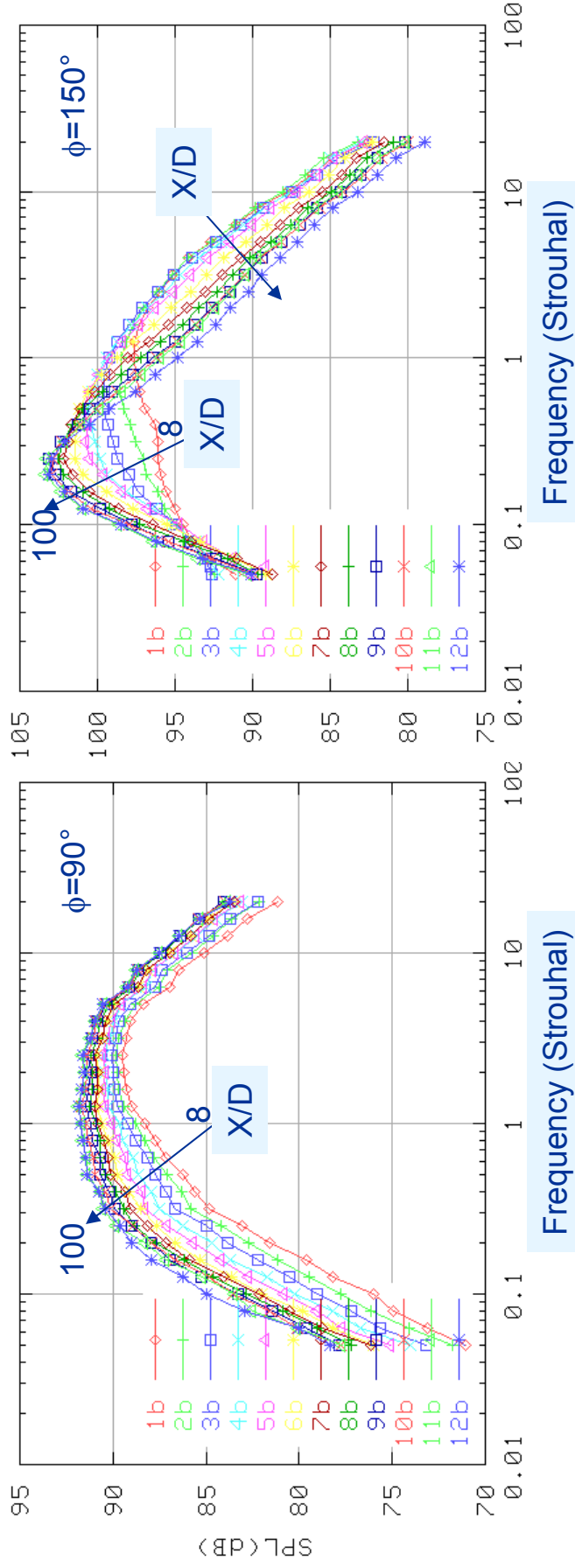
Polar angles from pilot POV!
 90°, 150° representative



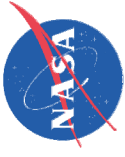
Baseline Data for CFD/CAA validation — Far-field Acoustics

- Objective: Verified far-field jet noise database, independent of facility
- Note dependence on far-field condition!

$M_j=0.9$, cold, normalized, lossless

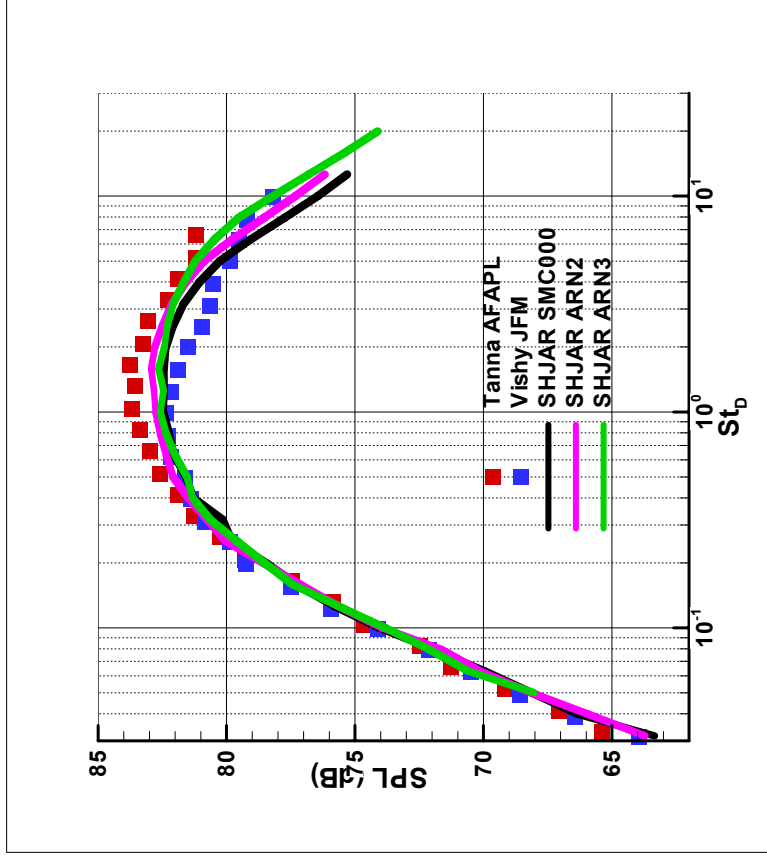


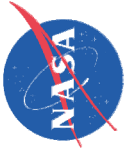
Far-field invariant $r/D > 50$



Effects of Scale, Upstream Nozzle Geometry

- SHJAR rig noise documented,
 - Well below this data.
- Variations found due to nozzle details.
 - Reynolds number dependence
 - State of turbulence in exit boundary layer!
 - Contraction ratio
 - Contraction rate
 - Length of contraction

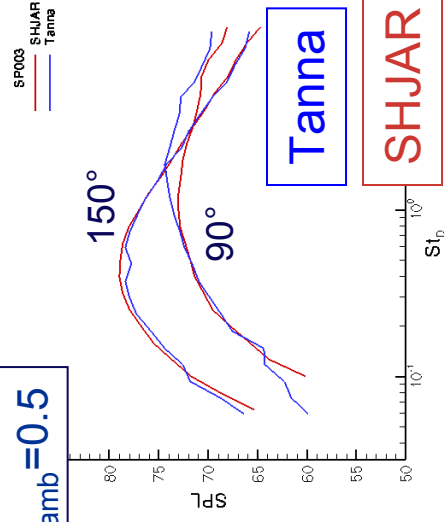




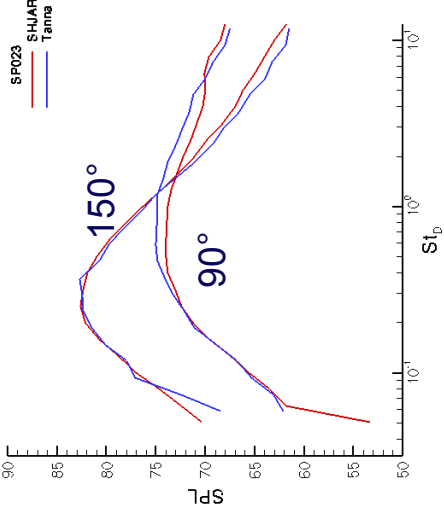
Comparison w/ Tanna Data for Hot Jets

Tratio=0.86

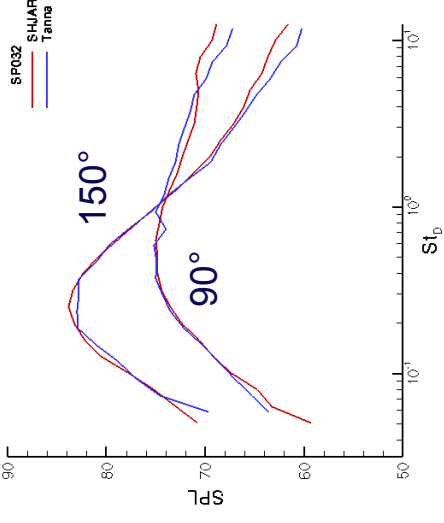
$V_j/c_{amb}=0.5$



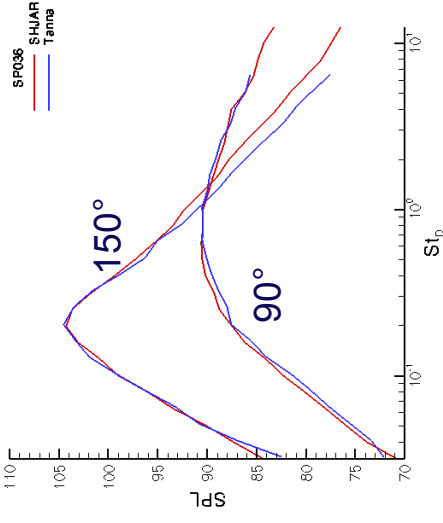
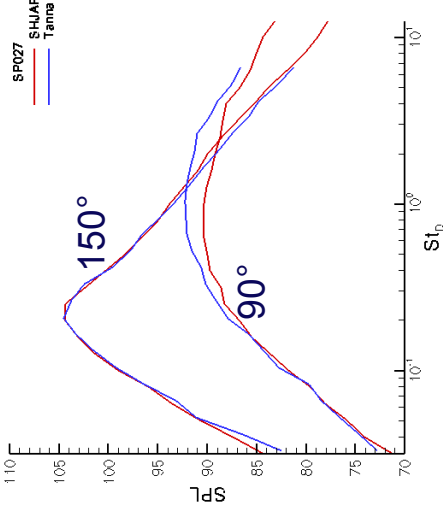
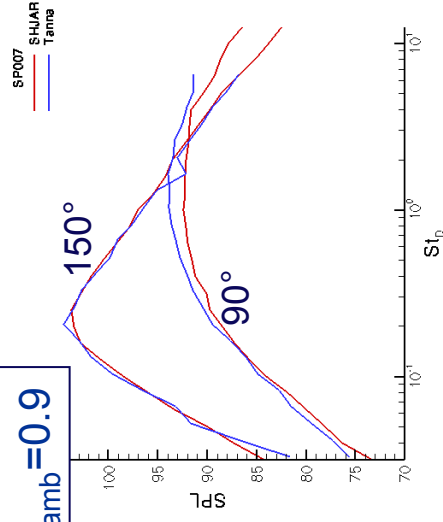
Tratio=1.76



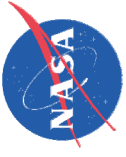
Tratio=2.27



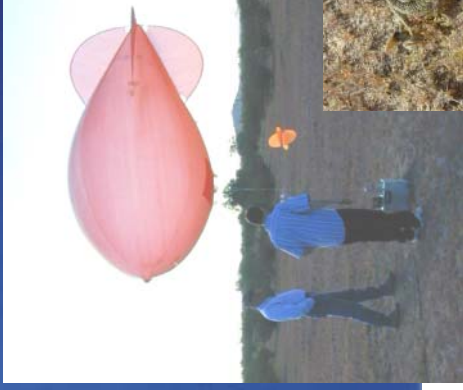
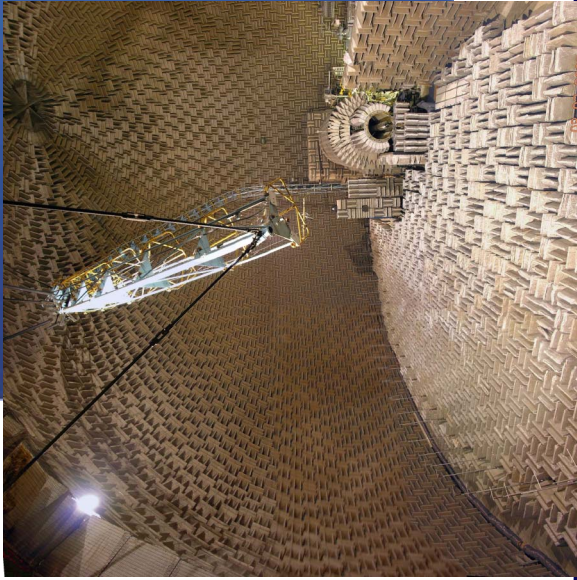
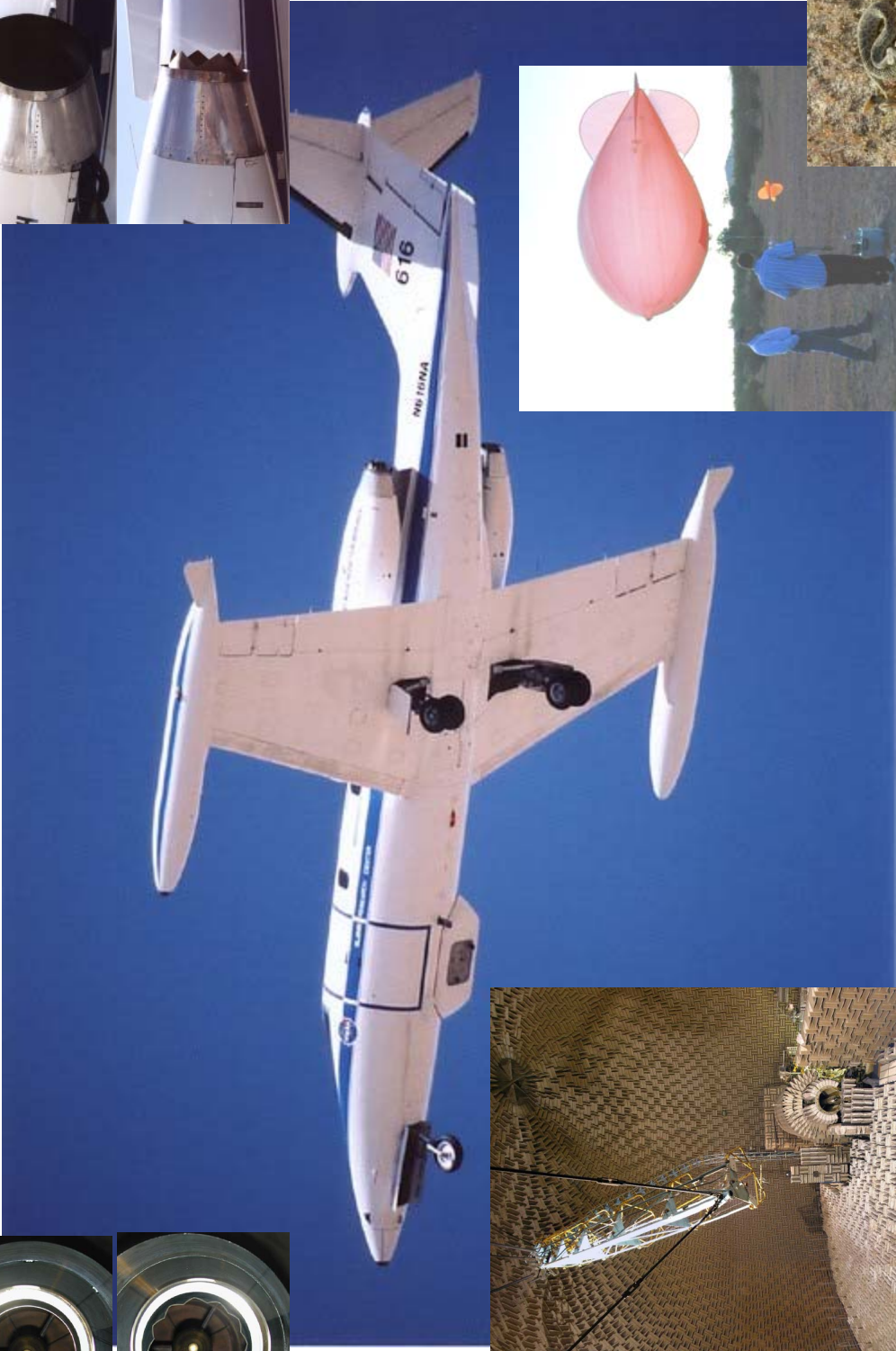
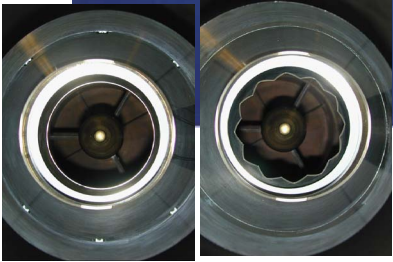
$V_j/c_{amb}=0.9$

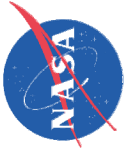


All data: third-octave, lossless, $r/D_j=40$

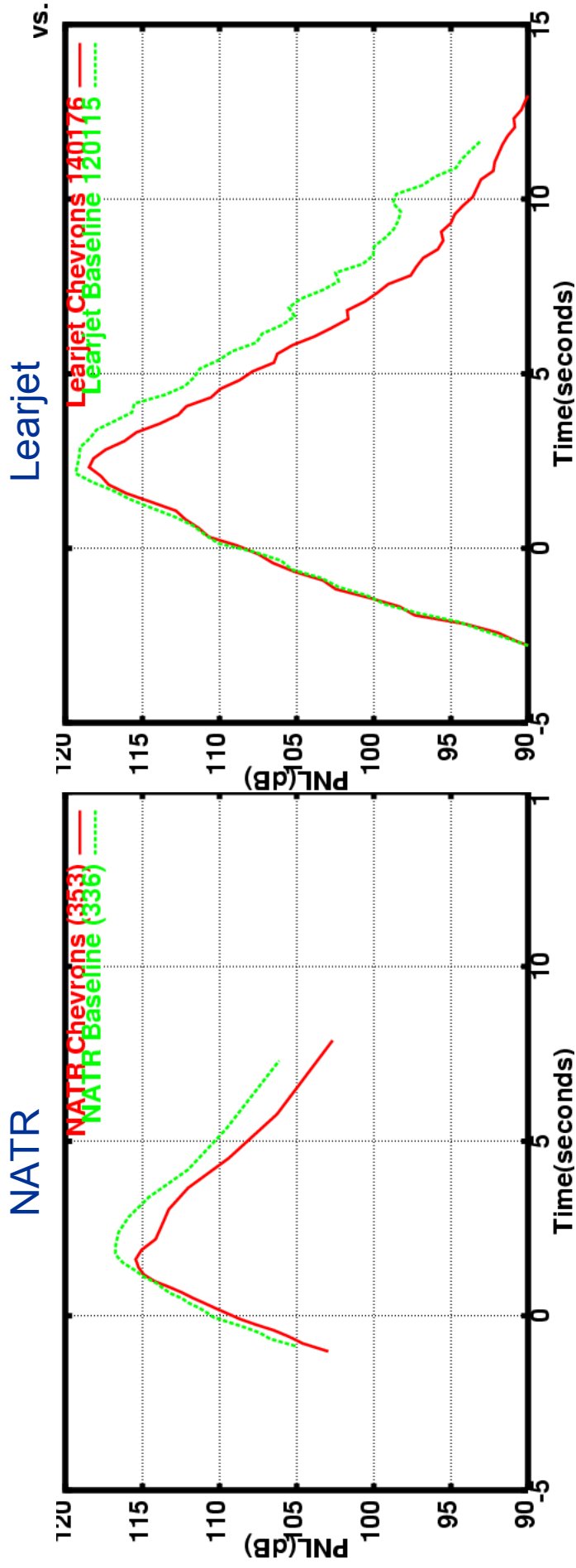


Flight Tests

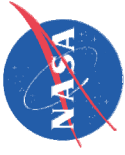




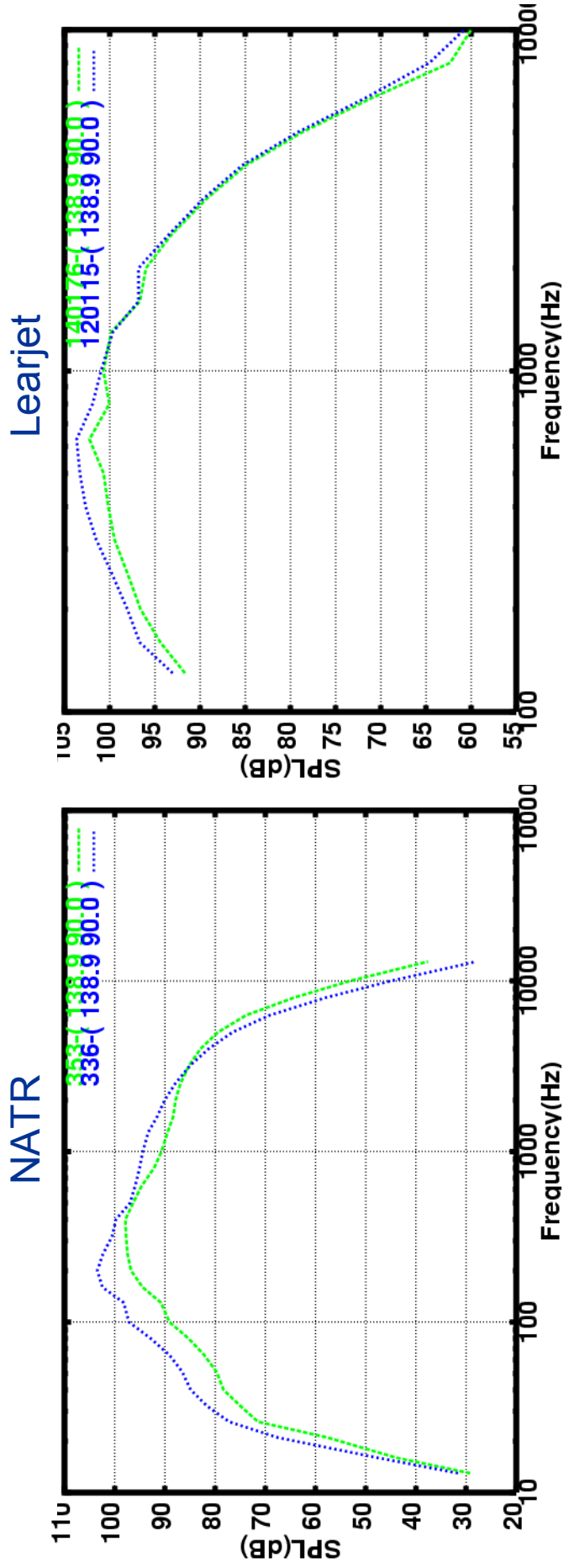
Chevron benefit comparison—PNL



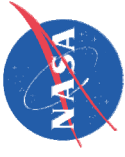
Nice agreement model to full scale!



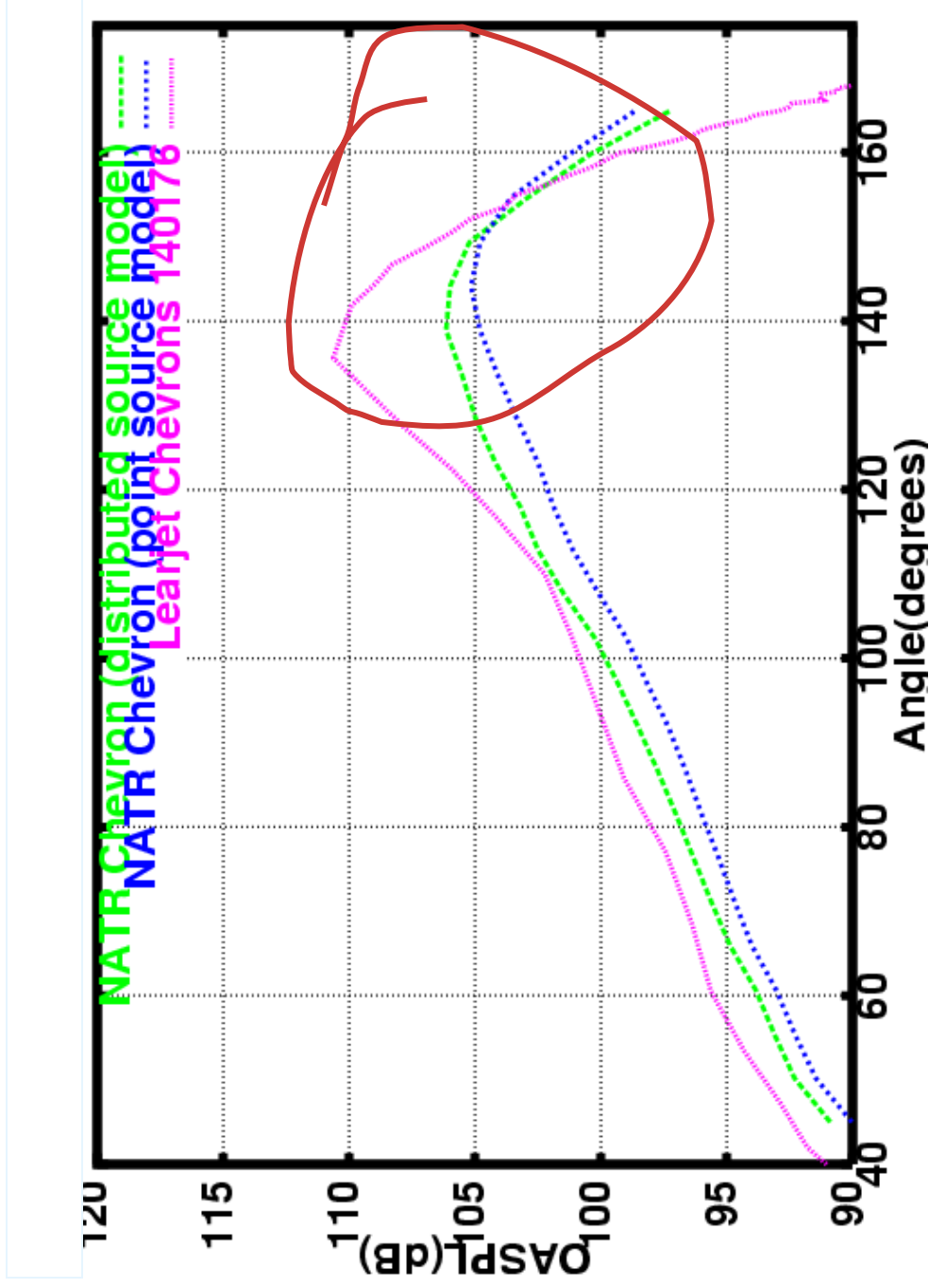
Chevron benefit comparison—SPL at peak PNL



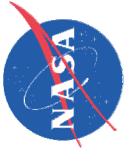
Passable recognition of spectral benefit.



Problem with Freejet Correction in Small Scale Source Distribution Assumption

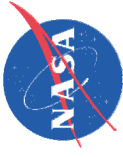


Issues with projecting to flight at angles near jet axis.



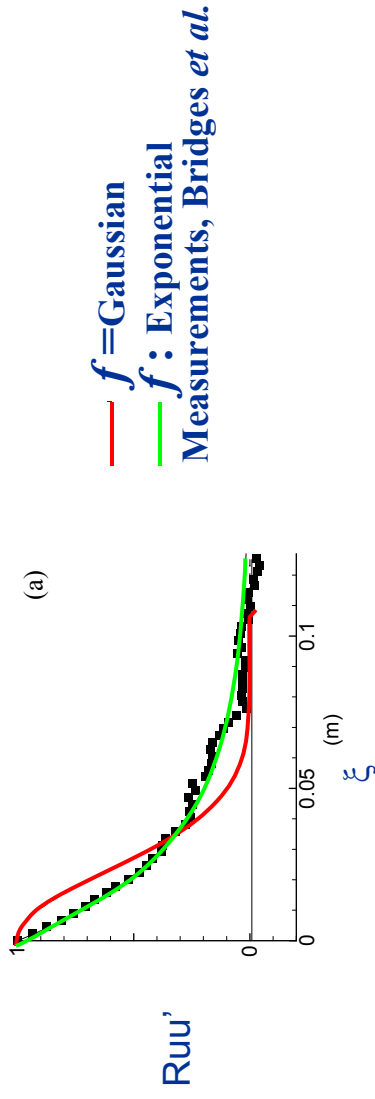
MGBK: A Lilley-Based Analogy

- Lighthill's original analogy cast equations as simple wave equation
- Lilley proposed accounting for convective character of source into wave operator.
- In 1976, Mani-Gliebe-Balsa created a jet noise prediction code which used this approach (MGB)
 - Many assumptions regarding parallel flow, source compactness.
 - Many models of turbulent quantities, such as space-time correlation matrix
 - Analytic asymptotic solution to Green's function for solution.
 - Critical mean and turbulence info from semi-analytical model for round jet.
- In 1989, Khavaran and Krejsa (NASA Glenn) picked up the MGB code and began by substituting CFD solutions for mean and turbulence fields for the semi-analytical solution used before.

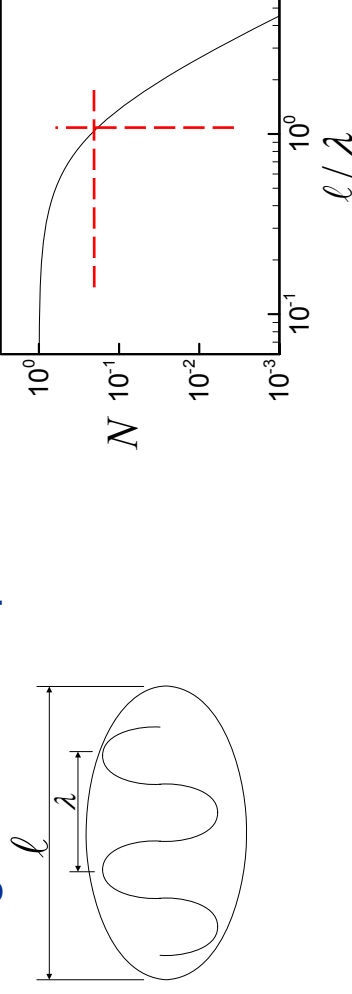


MGBK to JeNo: What Changed?

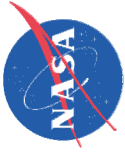
- Realistic two-point space-time correlation model.



- Accounting for non-compact sources.



- Accurate refraction by adjoint Green's function.

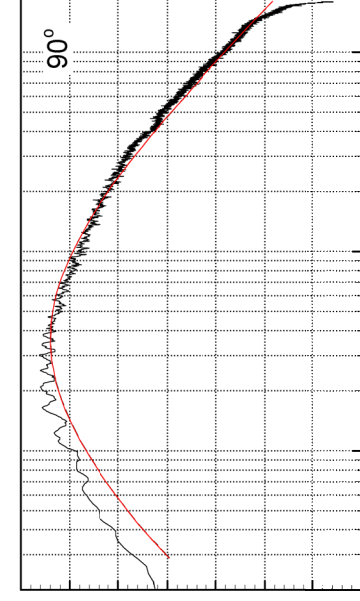
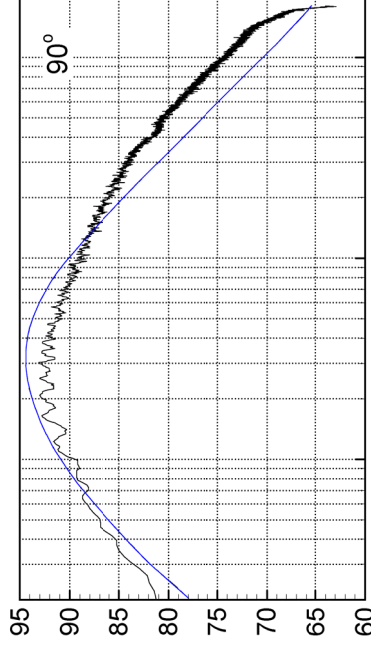


JeNo v1.0

- Validate all assumptions and models in acoustic analogy code.
- Result: Improvements in prediction code so substantial it warrants a new name—JeNo

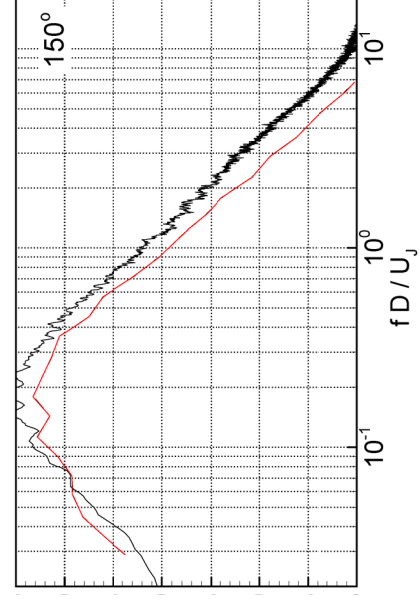
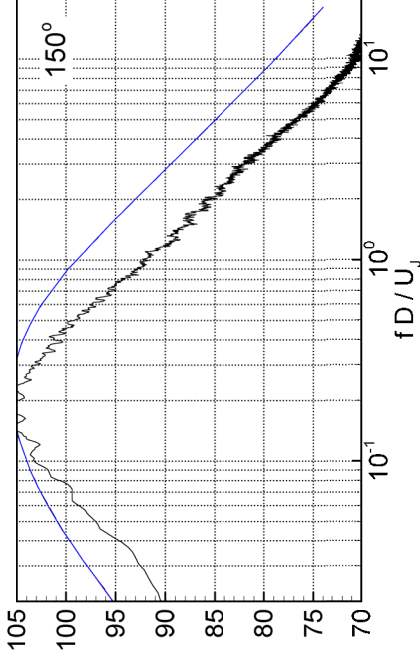
MGBK

JeNo

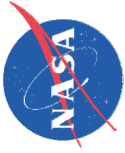


Ma=0.9 cold
(Tanna SP7)

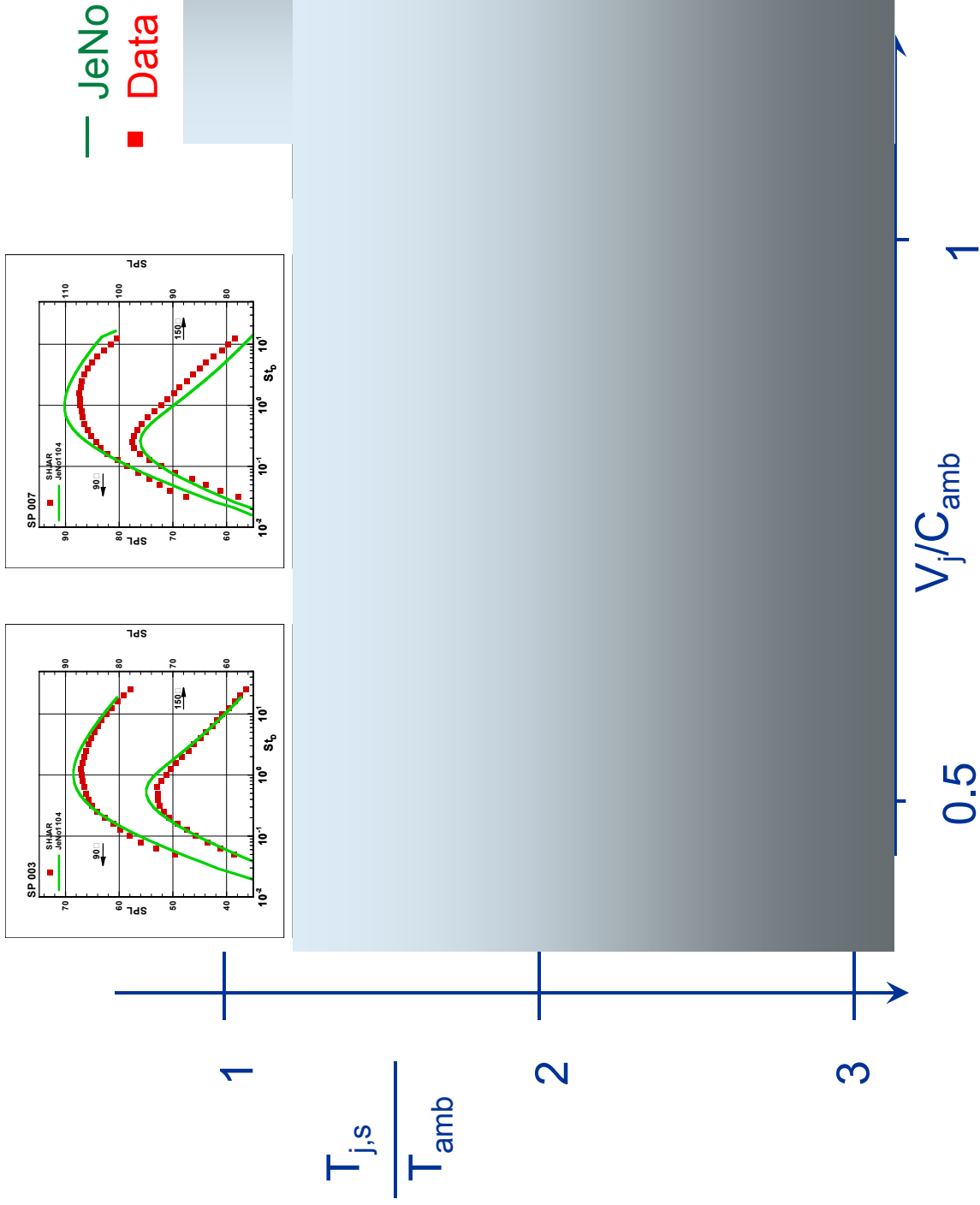
Good prediction
of cold jet noise
spectra at 90°

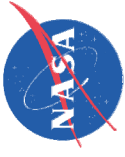


...and at aft
angles!



JeNo v1.0 Status—Nov 2005





Summary

- Experimental Diagnostics have played critical role
 - understanding jet noise physics,
 - guiding prediction code development,
 - checking assumptions
 - feeding model development
 - giving insight into noise reduction concepts
- Future Challenges
 - Temperature spectra for statistical models
 - Initial condition specification for LES
 - Refraction, Diffraction, Impingement